UNIVERSITY OF DELAWARE
CENTER FOR COMPOSITE MATERIALS
INTERNATIONALLY RECOGNIZED EXCELLENCE

MANUFACTURING OF COMPOSITE PARTS VIA VARTM

D. Heider

J. W. Gillespie, Jr.

UD-CCM

UD-CCM • 2 July 2003

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
26 AUG 2004	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Manufacturing Of Composite Parts Via VARTM	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Delaware Center for Composite Materials Newark, DE 19716**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001700, Advanced Materials Intelligent Processing Center: Phase IV., The original document contains color images.

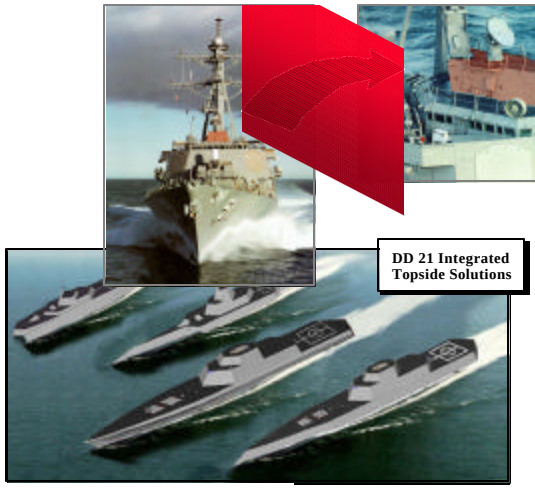
14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**48**	

Examples Of Current Composite Structures Fabricated Via VARTM

Vacuum Assisted Resin Transfer Molding (VARTM)



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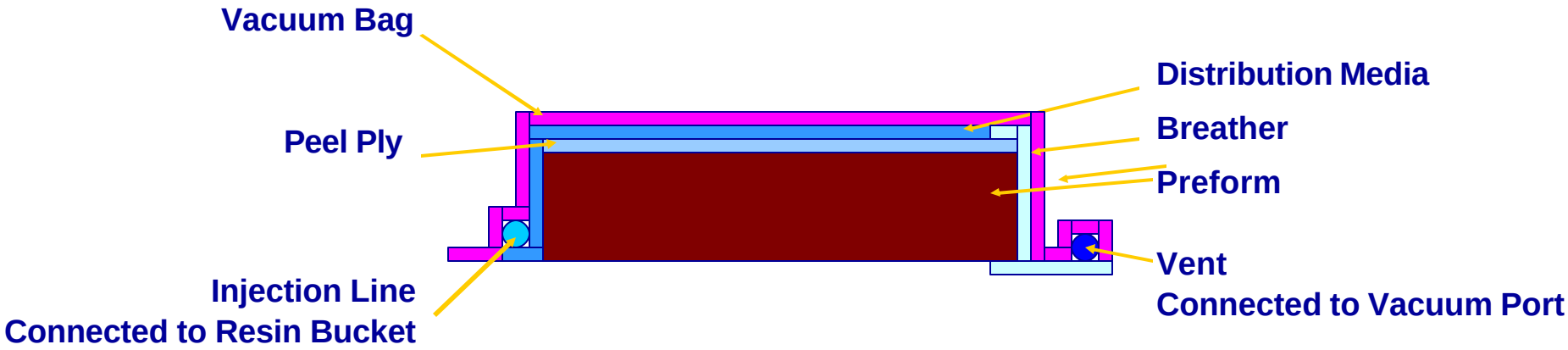
Vacuum-Assisted Resin Transfer Molding

Schematic And Processing Sequence



Processing Steps

PREFORM MANUFACTURING

- Precision Laser Cutter
- Preform Binding Station

IMPREGNATION STEP

- National VARTM Workcell
- Fully Automated Injection Station

CURE STEP

- Induction Heating
- Localized Resistive Heating

QA/QC

- Fiberoptic Health Monitoring
- Modal Analysis

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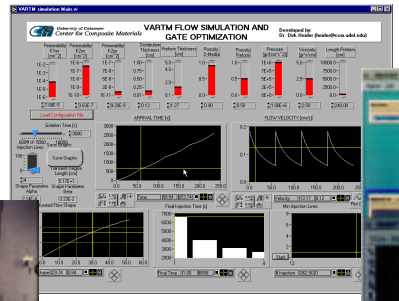
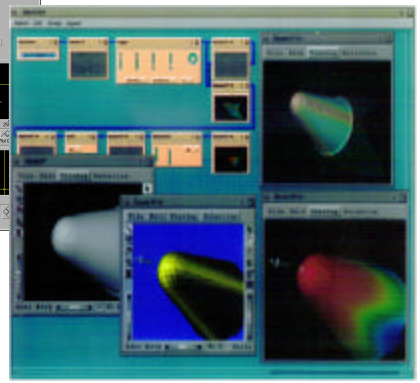
UD-CCM Intelligent VARTM Capabilities I

- **Resin Characterization and New Resin Development**
- **Preforming**
  - **Laser Cutter**
  - **3-D Preforms**
    - High-Performance (3TEX)
    - Binder (Solectria)
    - Complex Shape (Bally Ribbon)
  - **SMART-Preforms with integrated weaved sensors**
- **Permeability Station**
  - **2-D**
  - **Fully automated 3-D**

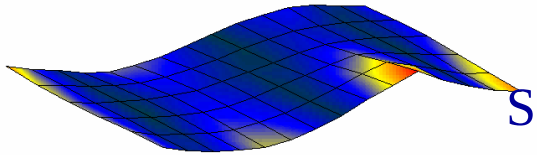




Simulation

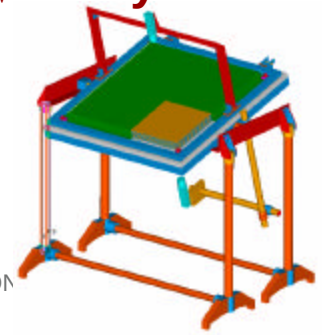
3-D Liquid I
(LIMS 5.0)

Analytical Tool for Design Optimization



Sensor

Flow and Cure



Tool-Mounted (reusable)

Embedded

Bag-Mounted

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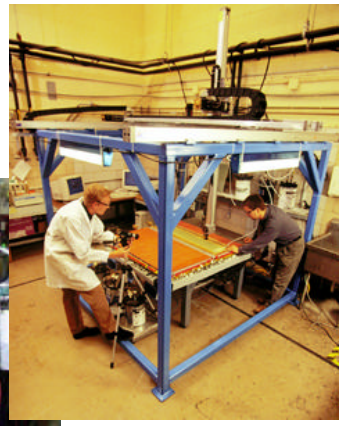
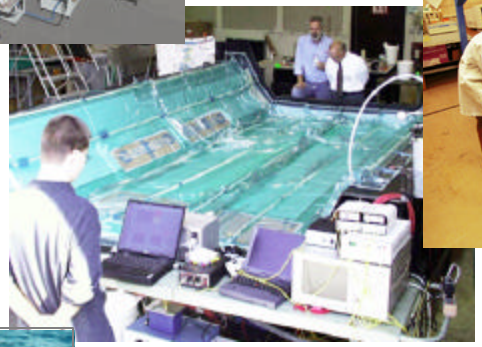
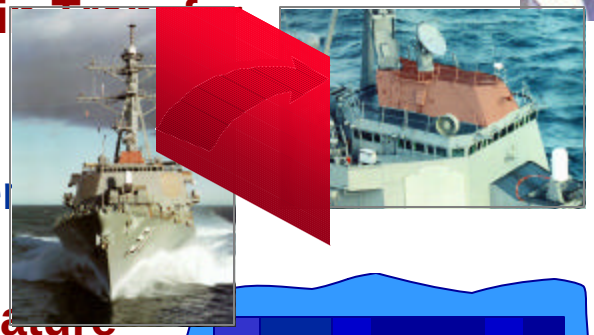
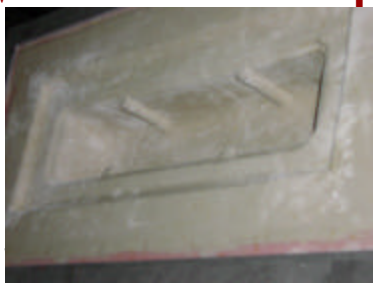
UD-CCM Intelligent VARTM Capabilities II

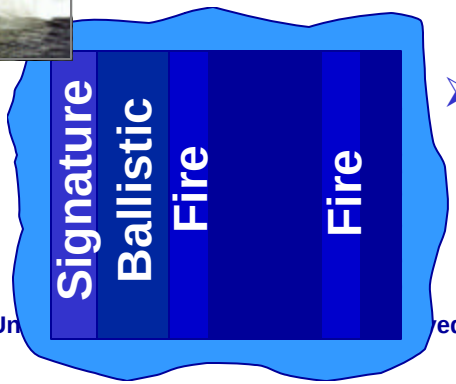
- **Control and Automation**
  - **Fully Automated Sequential Injection**
  - **Flow Rate Control**
- **Advanced VARTM Processing**
  - **RTM-like Parts**
    - Surface Quality
    - Dimensional Tolerances
  - **Co-Injection Resi… Molding**
    - In-Plane
    - Layer by Layer
  - **FASTRAC**
  - **Elevated Temperature**











- **Tooling**
  - **Rapid Prototyping**
  - **Rapid Water Solvable Tooling**
  - **Reusable Bagging**
- **Multifunctional Materials**
  - **Structural**
  - **Fire**
  - **Ballistic**
  - **Signal**

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Process Design Tool

No strong VARTM experience needed to make basic decisions on material and injection scheme

MATERIAL DATABASE
- Viscosity
- Permeability
- Infusion Temperature
- Gelation Time

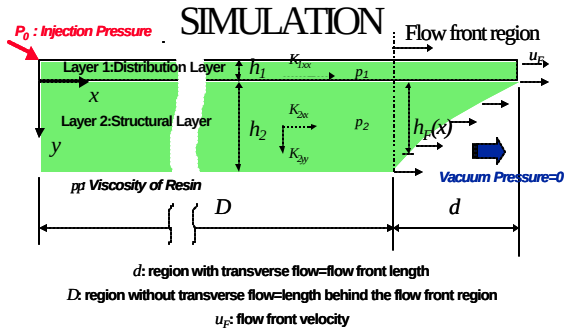
Down Select

PROCESS MODEL

Analyze

Database and Design capability can be increased over time

SIMULATION



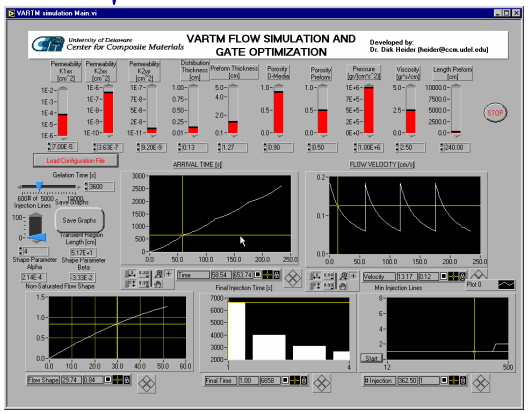
d: region with transverse flow=flow front length

D: region without transverse flow=length behind the flow front region

u_F: flow front velocity

Flow Behavior
- Infusion Time
- Number of Sequential Injection Lines
- Length of Non-Saturated Flow Region

GUI AND OPTIMIZATION



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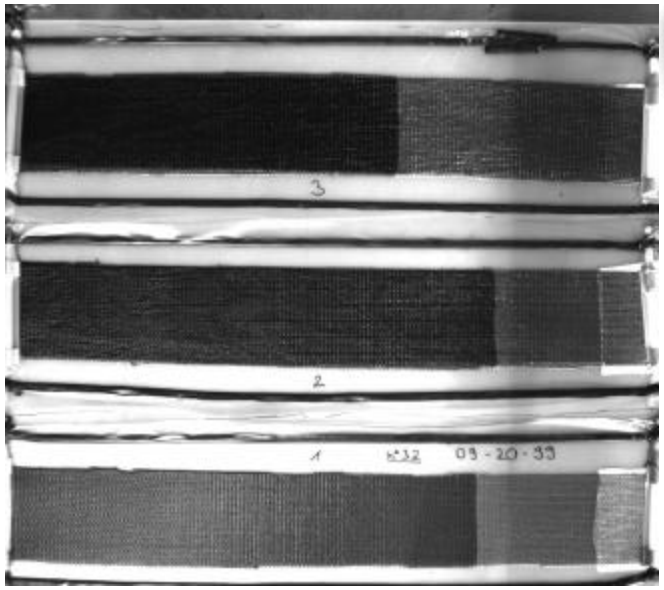
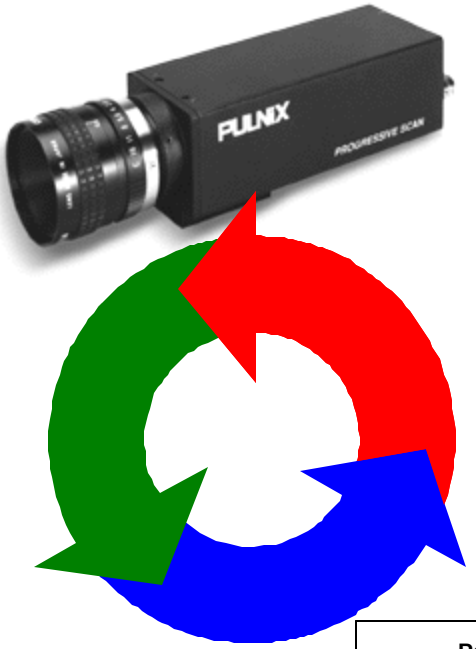
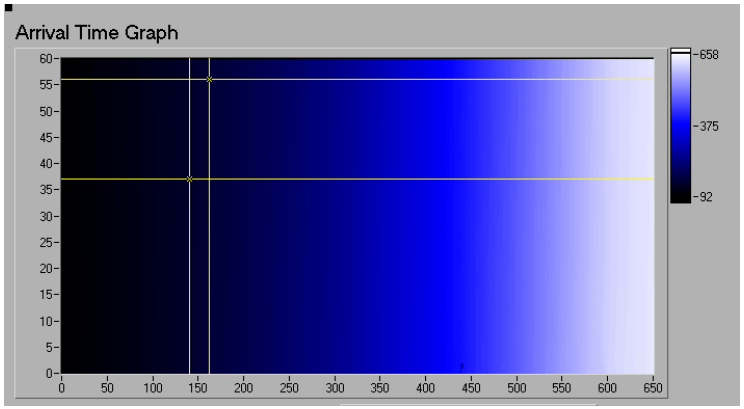
Automated Permeability Estimation (In-Plane Only)

Online Capturing of Flow-Behavior

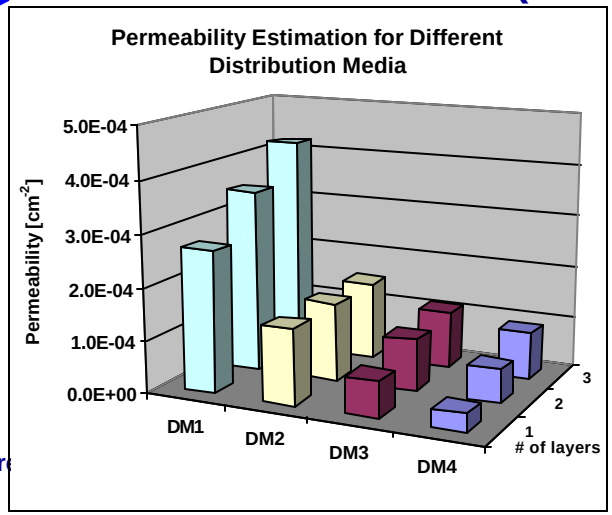






Post-Processing of Image Files

- Online/Offline
- Noise Reduction
- Arrival Time Calculation for all Pixels (1024x1024)



- Permeability Estimation (2D) for each preform/distribution media (Offline)
- Future work will incorporate online permeability estimation

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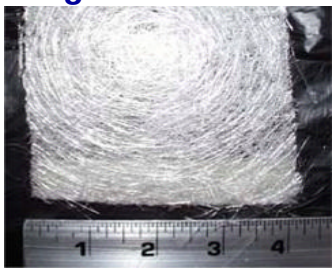
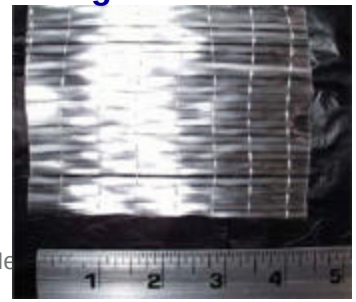
Database: Preform Permeability

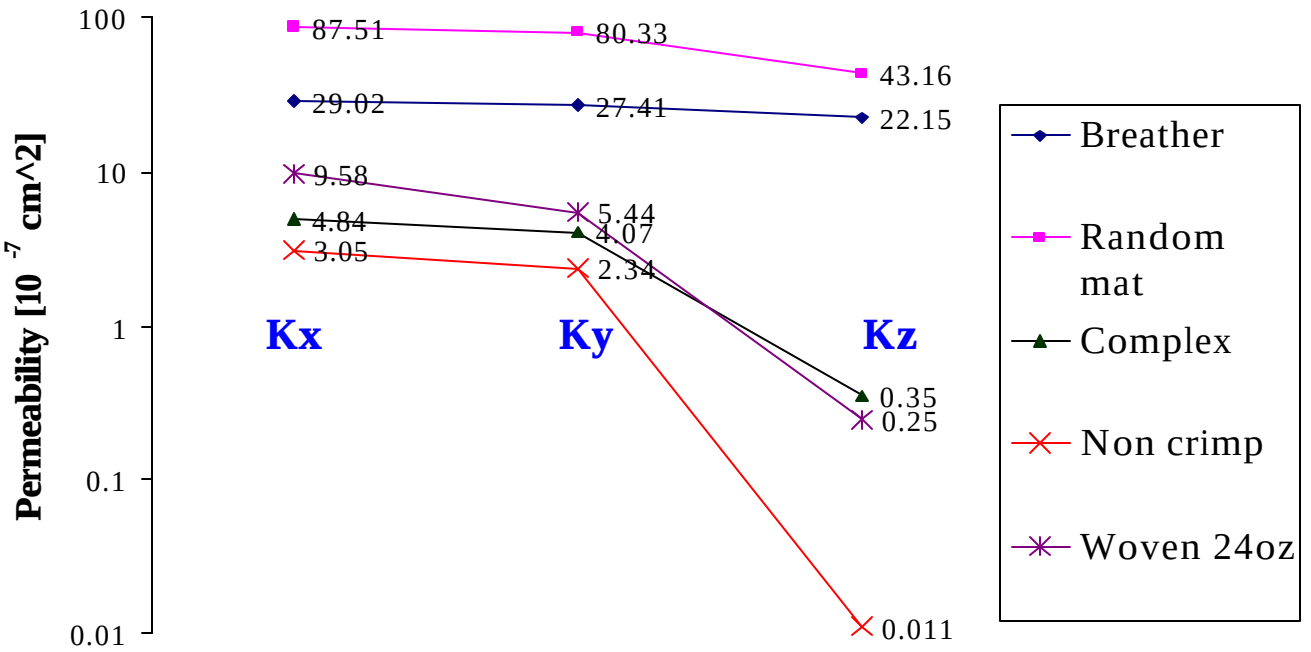
Breather:
Airtech Airweave N10
400g/m²

Random mat:
Vetrotex Unifilio 816
450g/m²

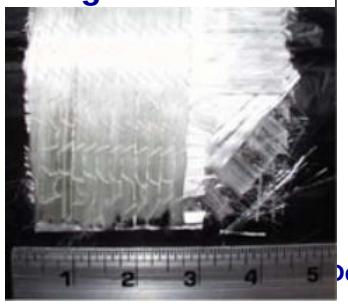


Non crimp :
320g/m²

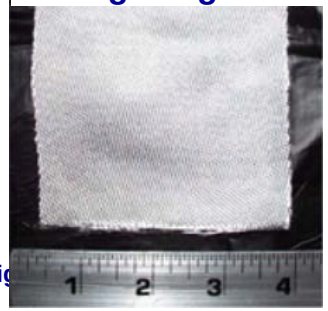




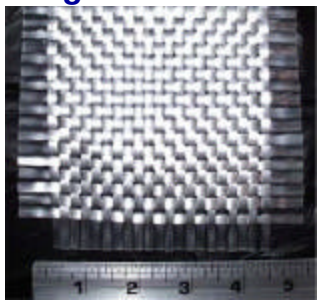
Complex:
Vetrotex Stitchment
2400g/m²



Woven:
Boeing 300g/m²



Woven:
Vetrotex 324
800g/m²



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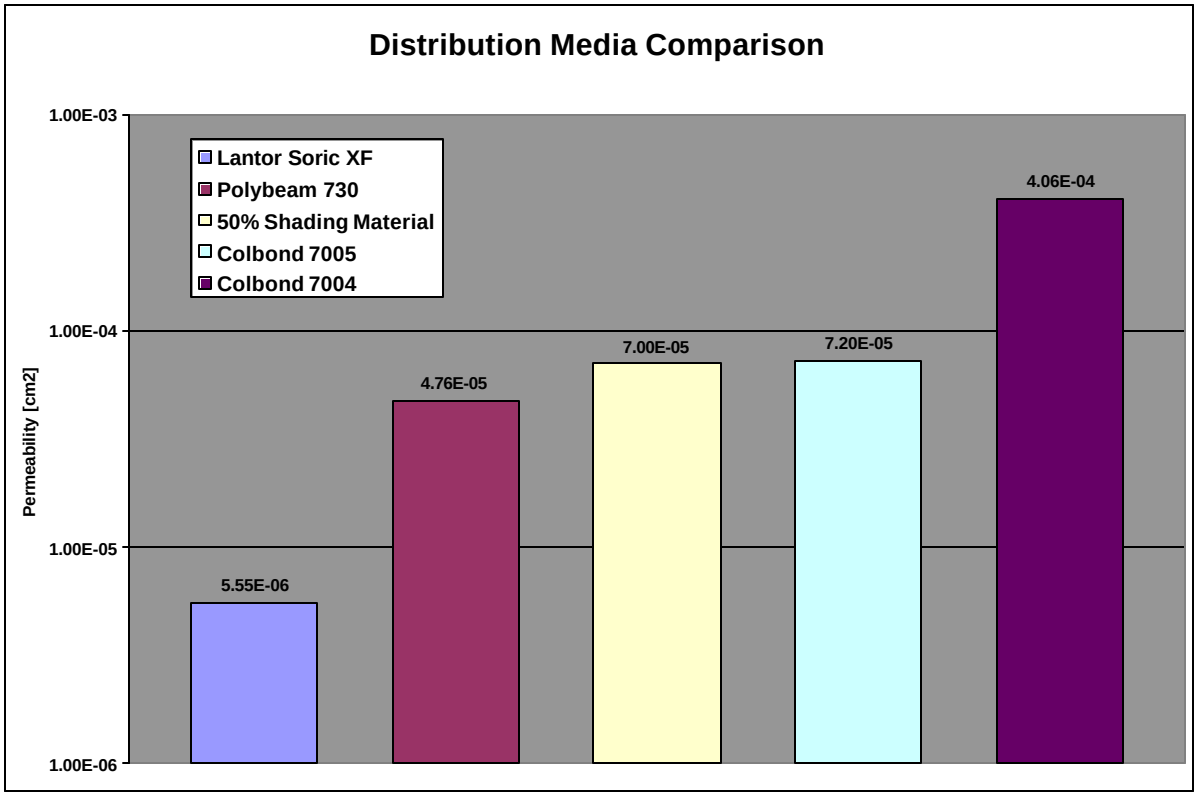
Added Permeability Data to Database of Commercially Available Distribution Media

Data Courtesy of Gaetan Denis



Database includes now 5 Distribution Media (4 more in progress)
Design tool chooses DM based on lead length and flow times

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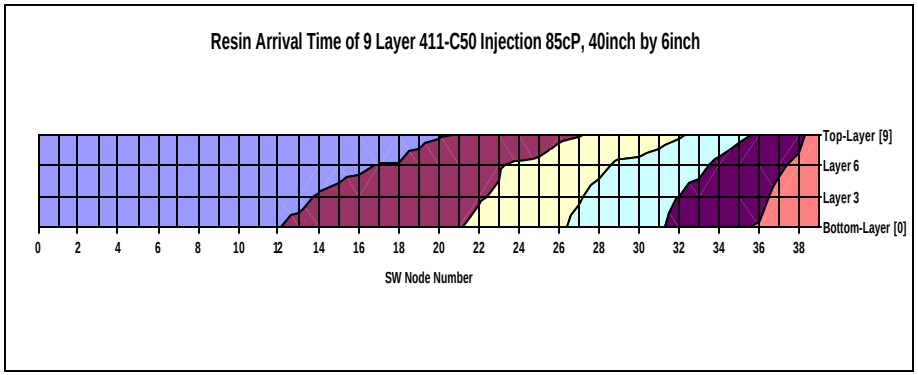
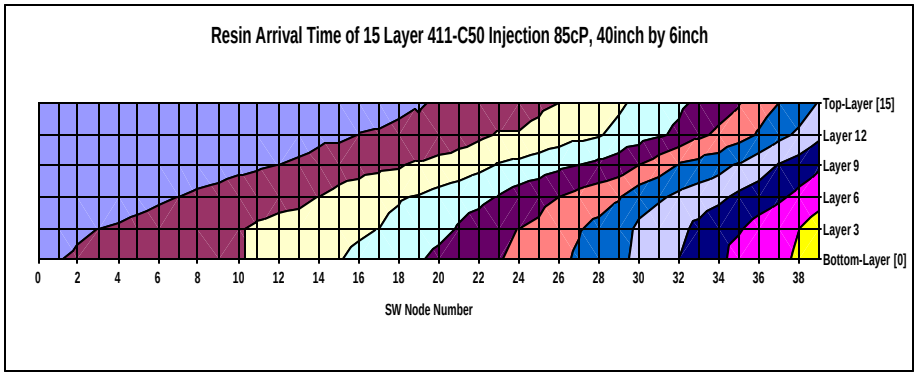
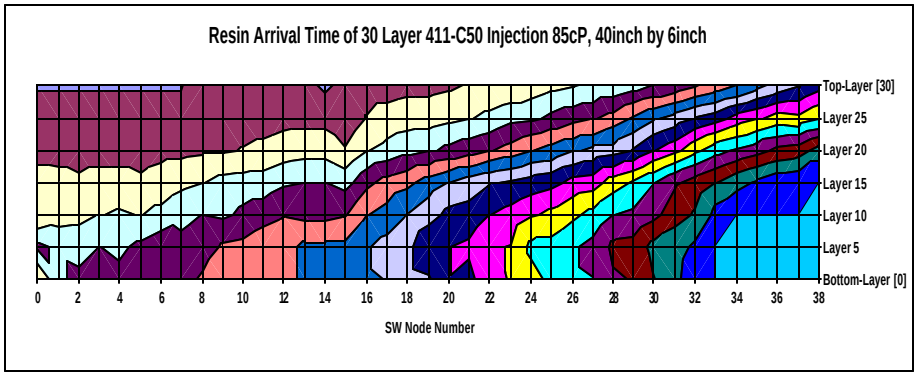
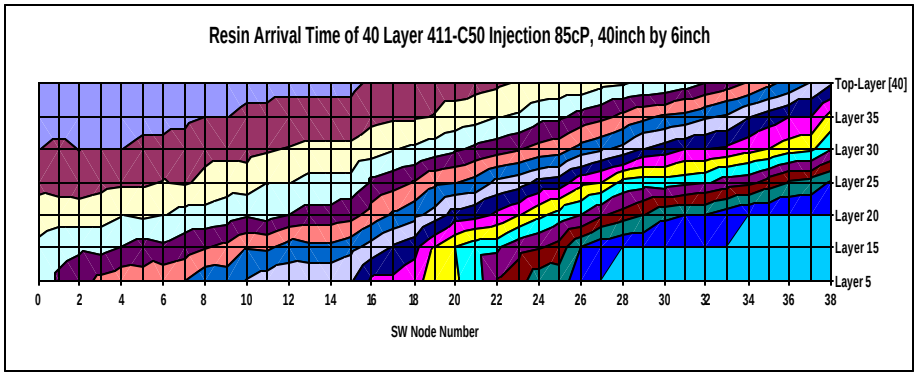
Resin Arrival Times Measured By SMARTWeave









- **Increase of non-saturated flow region with number of layers**
- **Resin arrival times increase linearly with number of layers**
- **Important VARTM feature ==> Elimination of dry spots during sequential injection with correct opening of injection ports**
- **Optimization of injection length (sequential injection) is important to reduce cycle times, especially for thick-section and large-scale composite parts**

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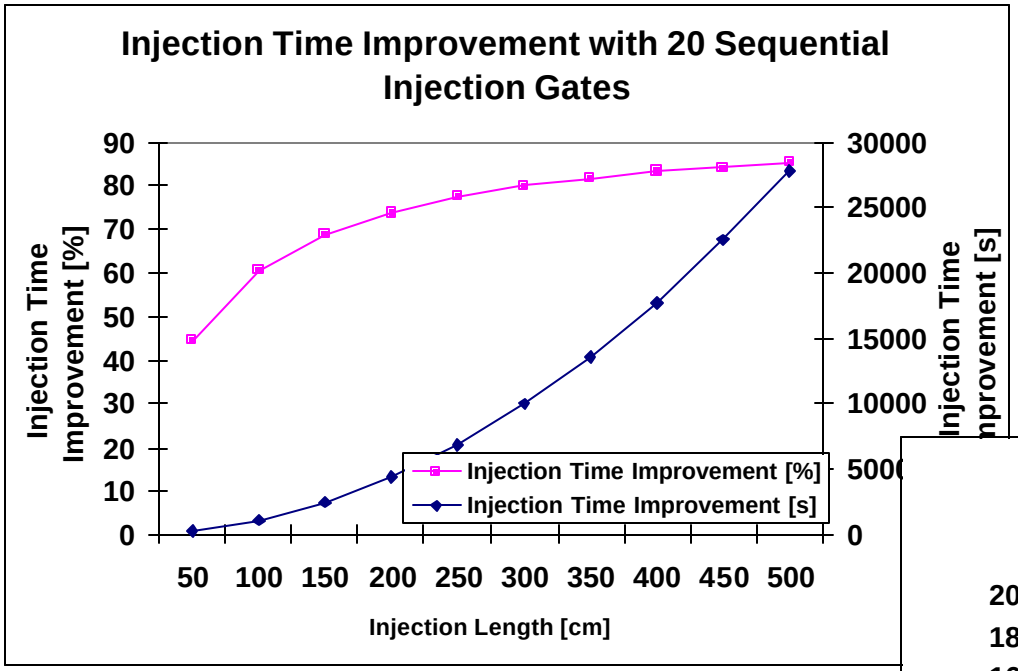
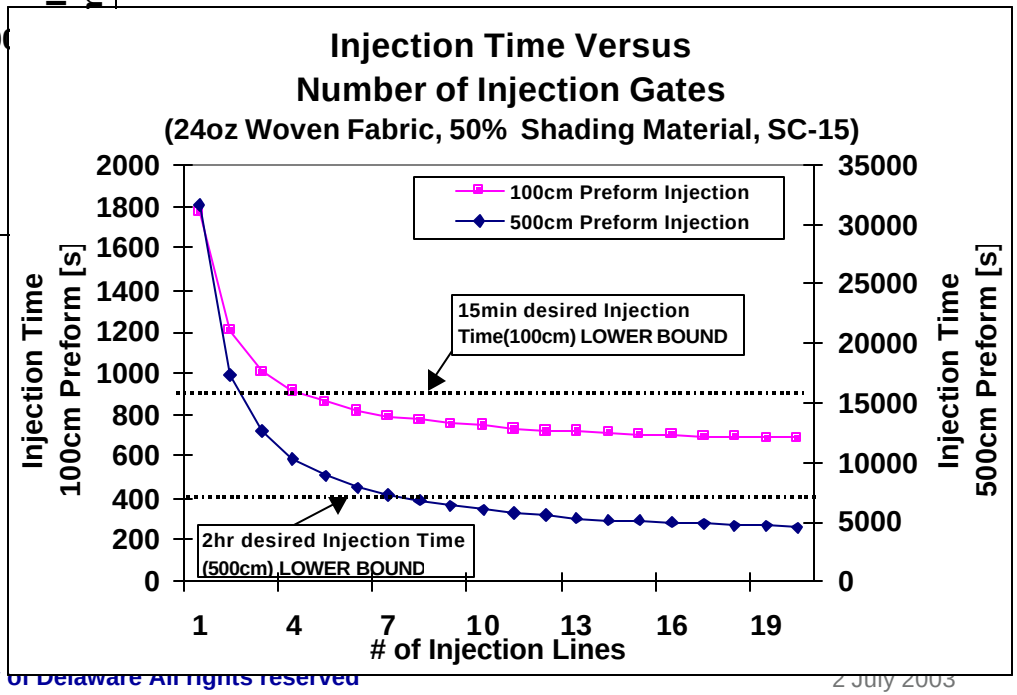
Influence of Sequential Injection Lines





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Decisions Required for an Optimal Sequential Injection of Large Parts

1. A minimum number of inlets (lower bound for the number of inlets) are required to assure fill times are less the gel time to ensure complete fill.
2. Increasing number of inlets will reduce cycle time but add cost (additional bagging setup (labor) and hardware requirement, resin waste, etc.). The minimum spacing and thus upper bound for the number of injection lines should be related to the flow front lead length. Analytical studies have shown that the lead length is strongly dependent on the permeability of the distribution media and the preform permeability and thickness.
3. The optimum timing for opening of the sequential injection gate is when no dry-spot can develop under the injection gate. Opening of the injection when the tool surface under the gate is wetted ensures complete wet-out and a minimum penalty on cycle time (optimum opening would be shortly before the tool surface under the gate is wetted out).

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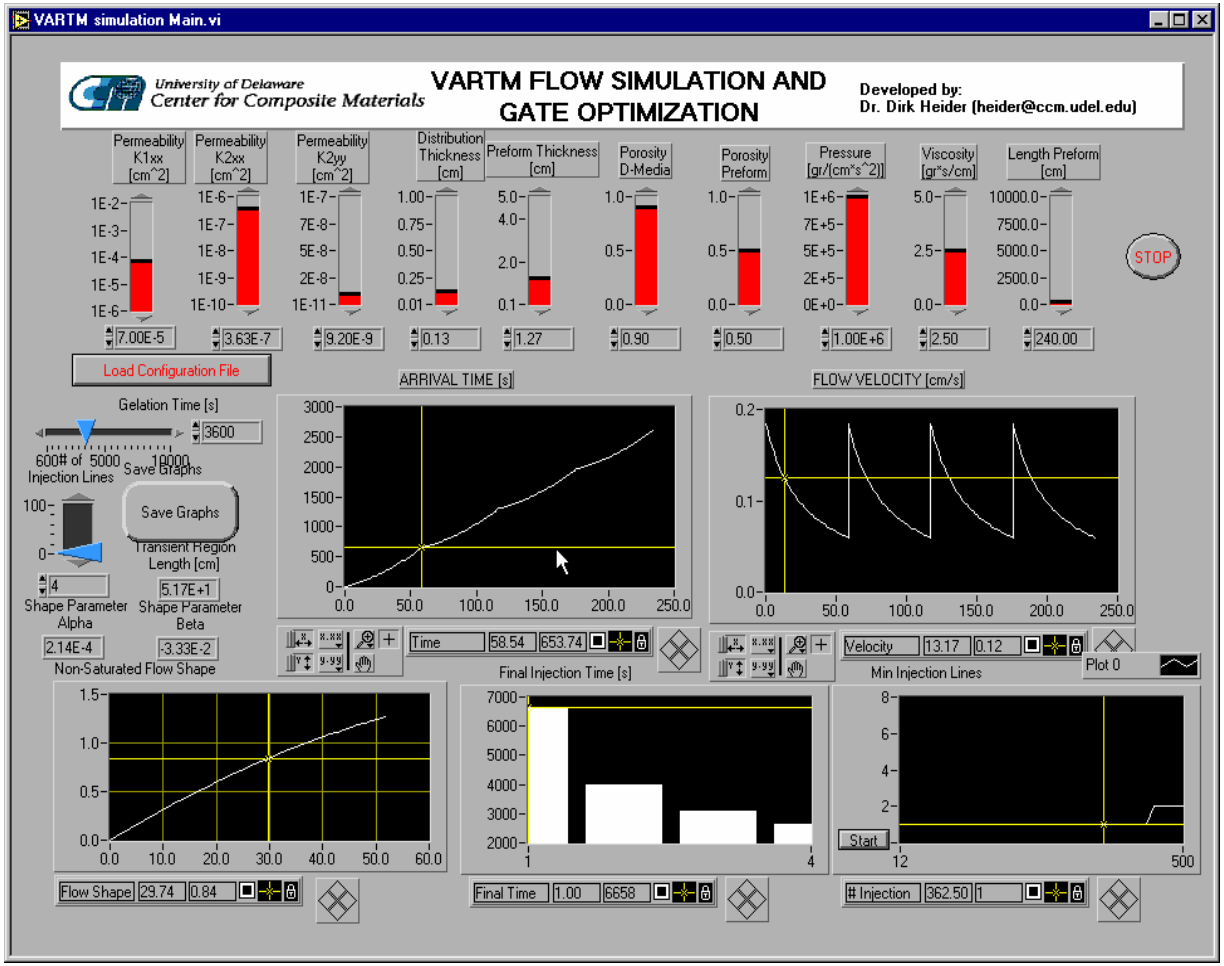
Design Tool Demonstration



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Design Example: Hull Section

BASELINE:

Fabric: 42 layers of 24oz. Woven Fabric

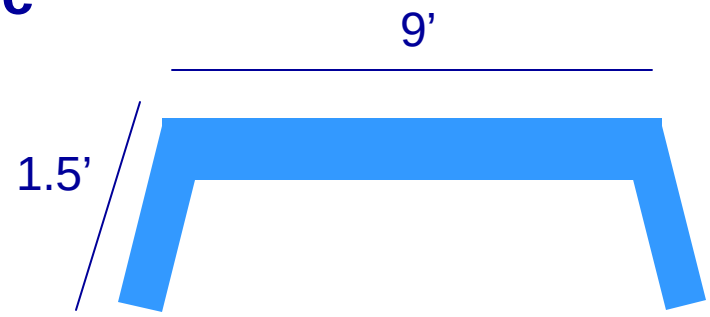
Resin: DOW Derakane Momentum 411-100 Resin

Distribution Media: 50% Shading Material

Part Dimension Hull Section

- **12 feet by 8 feet by 1 inch**

Infusion time approximately 30 minutes



Center injection scheme will reduce one dimension by a factor of 2

We assume injection along the width of the part

- **Problem reduces to an infusion of a 6 feet part**

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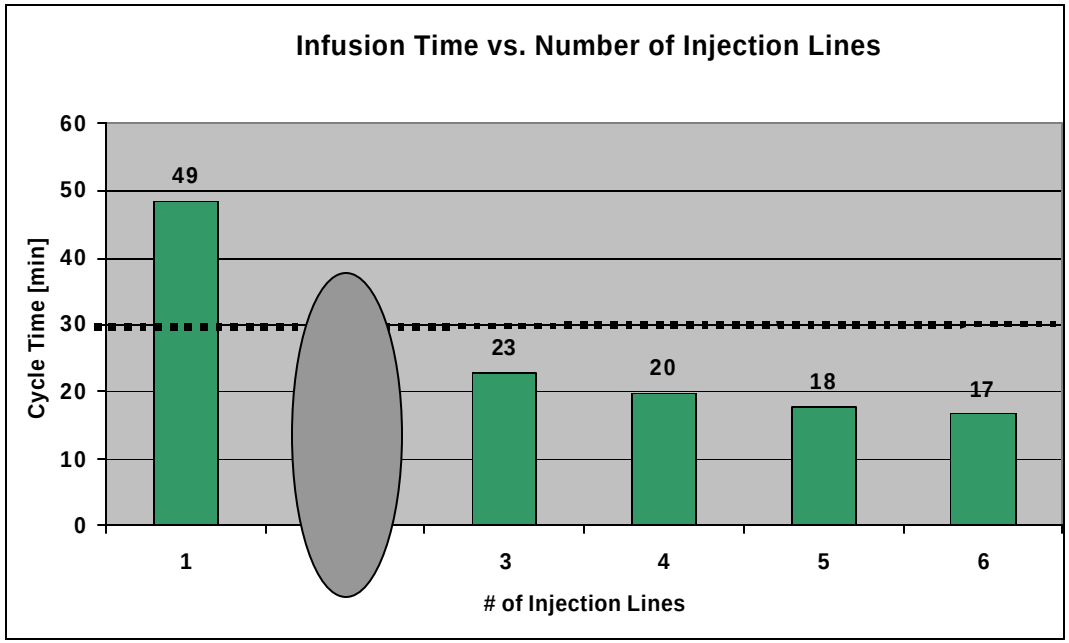
Design Summary

Minimum spacing given by non-saturated lead length ~50cm

- ➔ **A maximum of six injection should be used**



If total infusion time should be below 30 minutes then the optimum number of inlets equals TWO (Total of three) !!!

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Design Example II: Hull Section

BASELINE:

Fabric:40 layers of 24oz. Woven Fabric

Resin: Applied Poleramics SC-15 Resin

Distribution Media: 50% Shading Material

Part Dimension Hull Section

- **12 feet by 8 feet by 1 inch**

Infusion time approximately 90 minutes (3x Derakane 411-100)

Change in resin type results in increase in viscosity but allows longer gelation and infusion time

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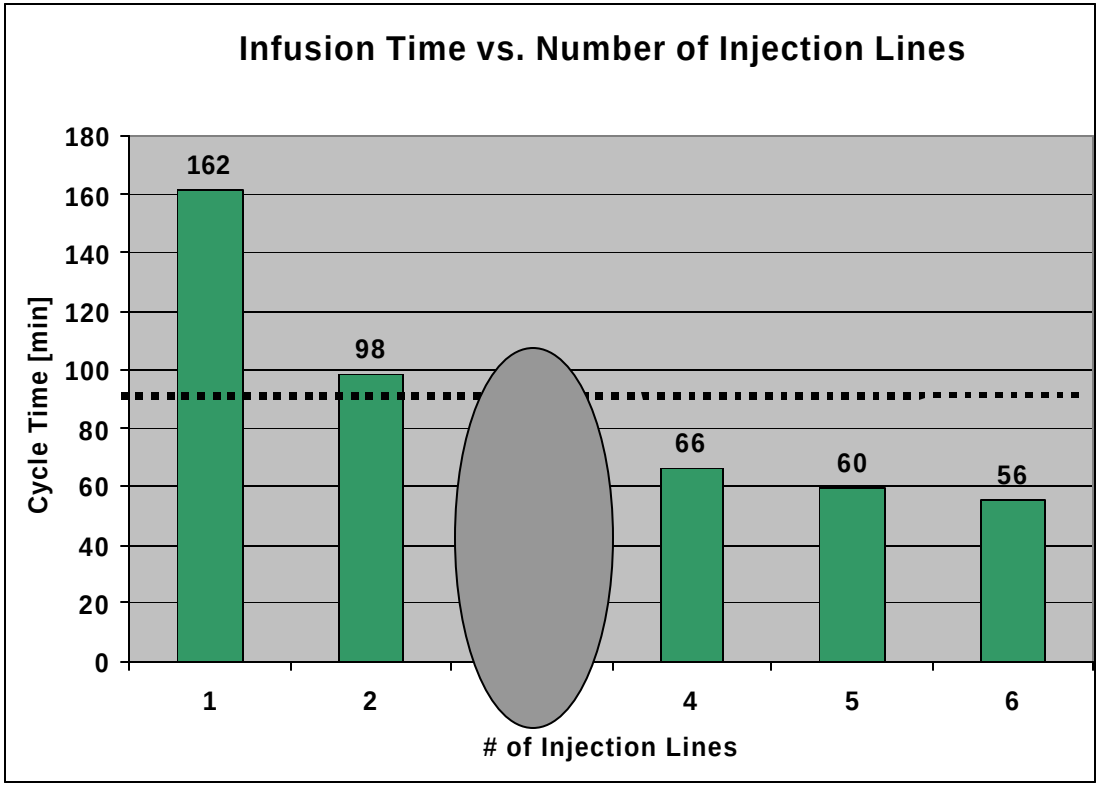
Design II

Change in resin type results in increase in viscosity but allows longer gelation and infusion time



If total infusion time should be below 90 minutes then the optimum number of inlets equals THREE !!!

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Design Example III
Hull Section

BASELINE:

Fabric: New fabric with Twice the Permeability

Resin: Applied Poleramics SC-15 Resin

Distribution Media: 50% Shading Material

Part Dimension Hull Section

- **21 feet by 8 feet by 1 inch**

Infusion time approximately 90 minutes

Change in fabric type results in increase in permeability decreasing infusion time

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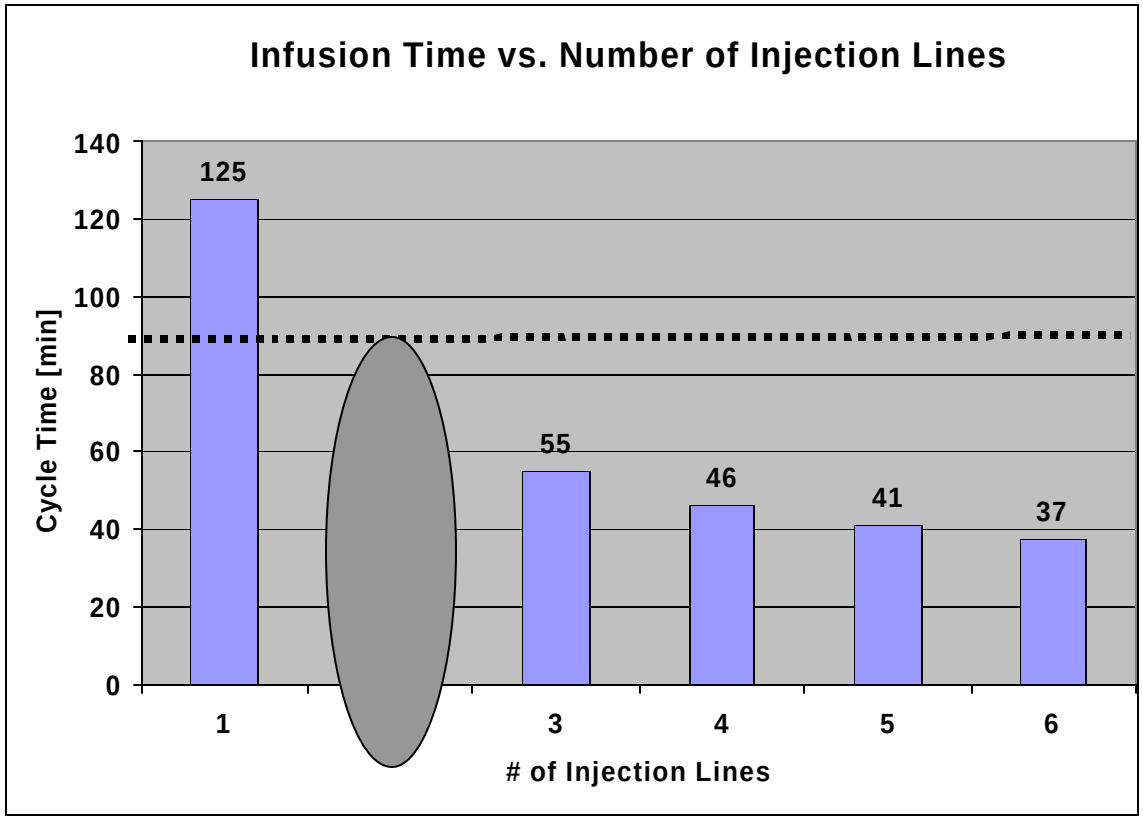
Design III

Change in fabric type results in increase in permeability allowing faster infusion



If total infusion time should be below 90 minutes then the optimum number of inlets equals TWO !!!

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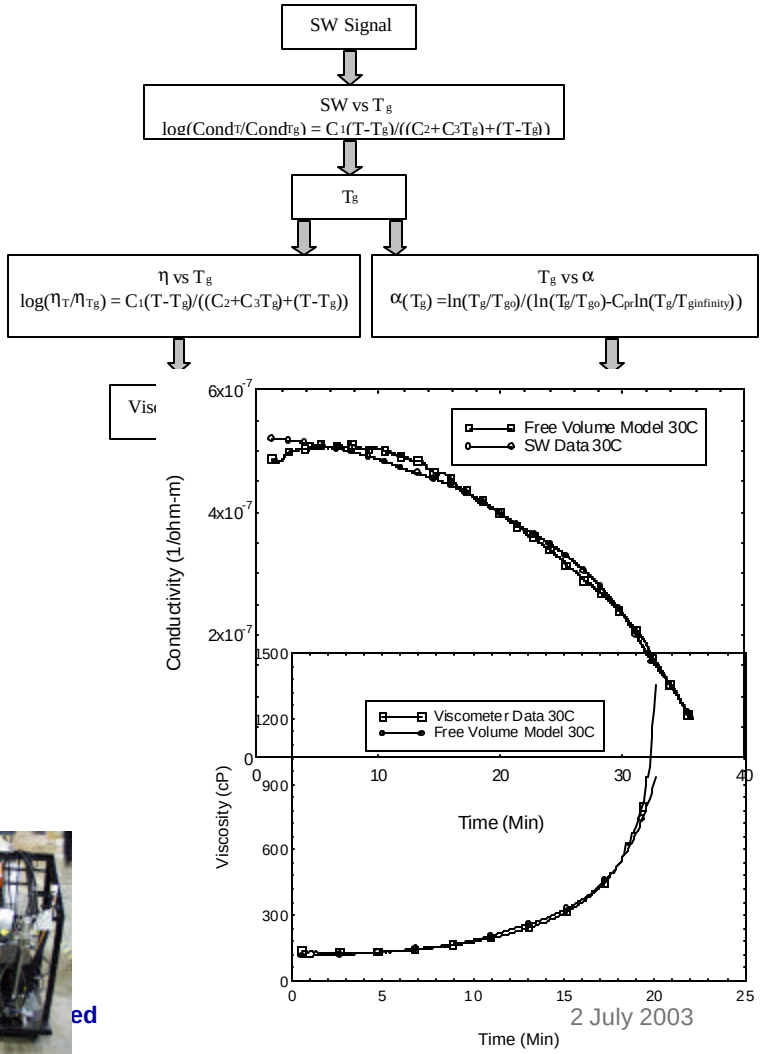
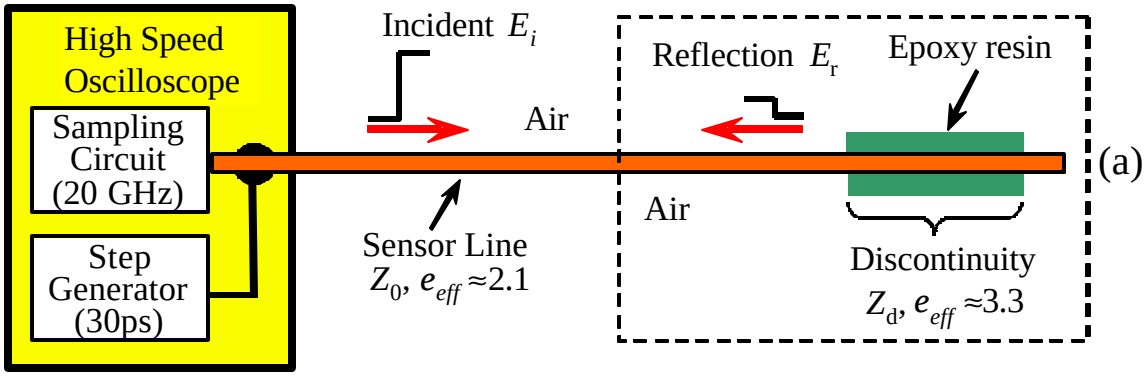
SMARTWEAVE and SMARTMolding Sensors

- **Low cost sensors measures conductivity of resin**
  - **SMARTweave (patented by ARL) uses embedded wires, creating nodal measurement points**
  - **SMARTMolding sensors are tool-mounted**
- **Resin arrival**
- **Gelation behavior**

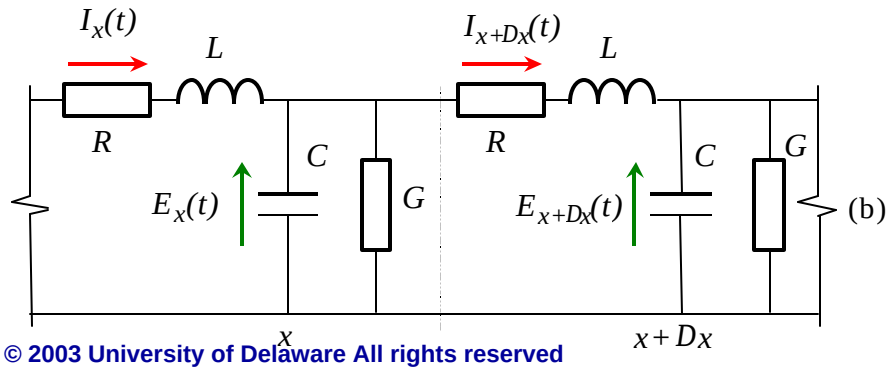


Electric Time Domain Reflectometry (E-TDR) Approach

E-TDR is a method of sending a high-speed electrical pulse along a transmission line, and detecting reflections returning from impedance discontinuities within the line. In other words acquisition speed (50 GHz) is so fast that is possible to analyze transition even in short (10mm) electromagnetic circuits.



Schematic of the E-TDR technique (a) and equivalent circuit diagram of the transmission line (b).



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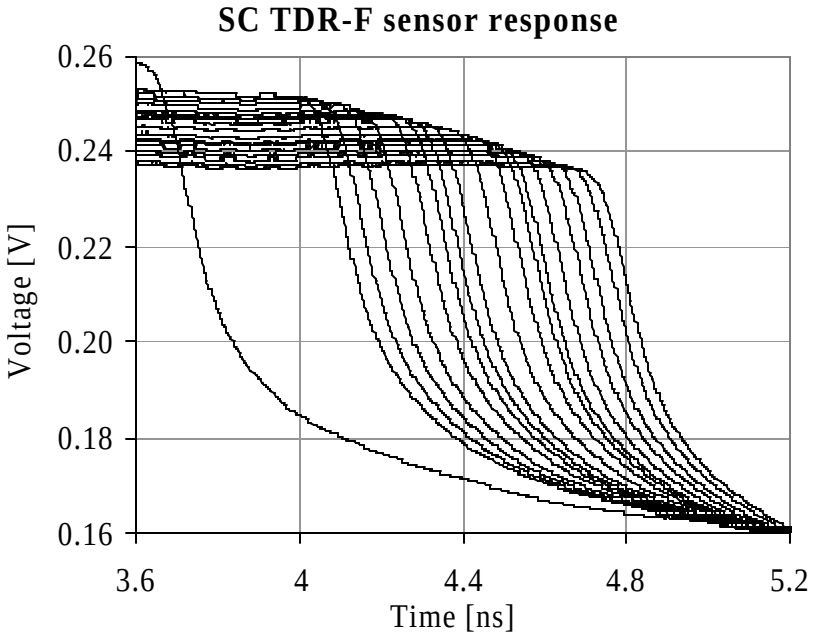
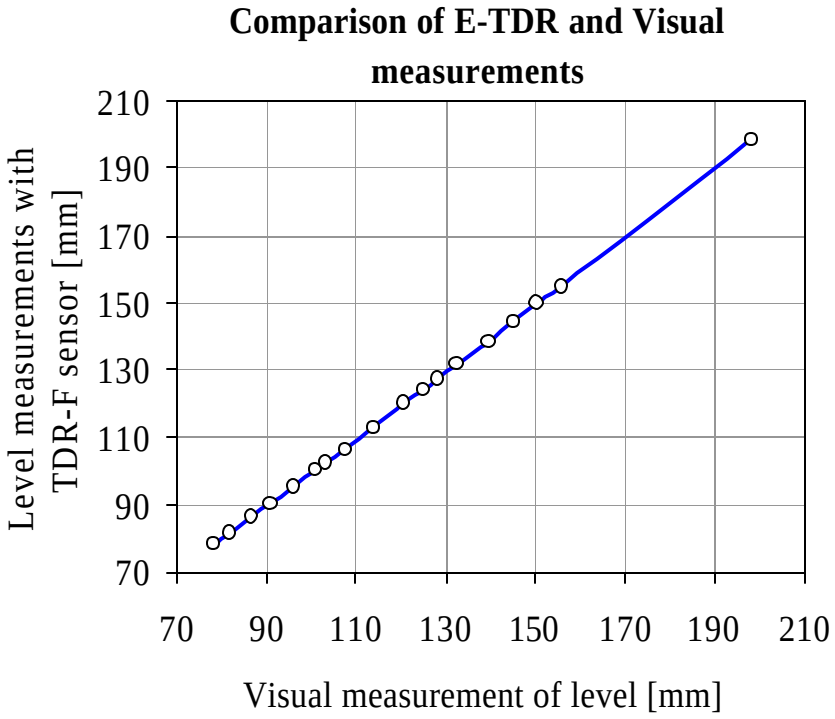
Example: TDR Flow Measurement System Results



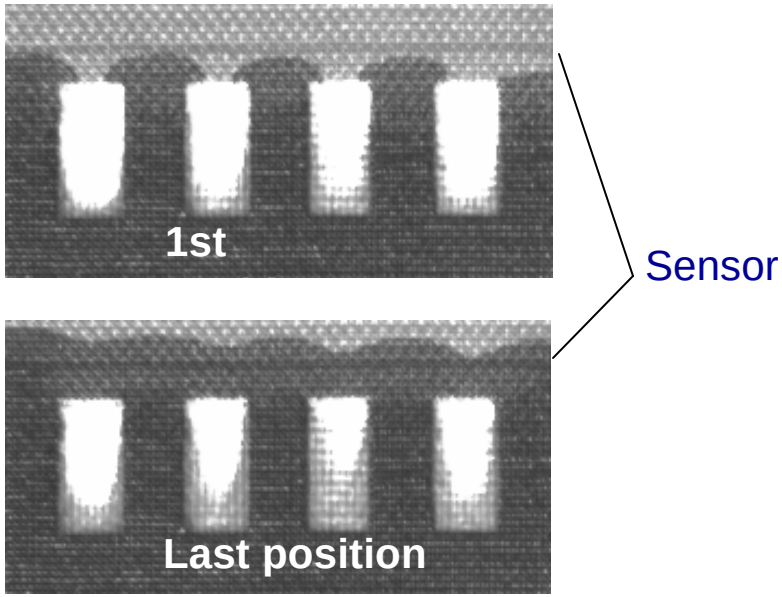
Arrival time of E-TDR sensor during level change in the U-shaped tube.

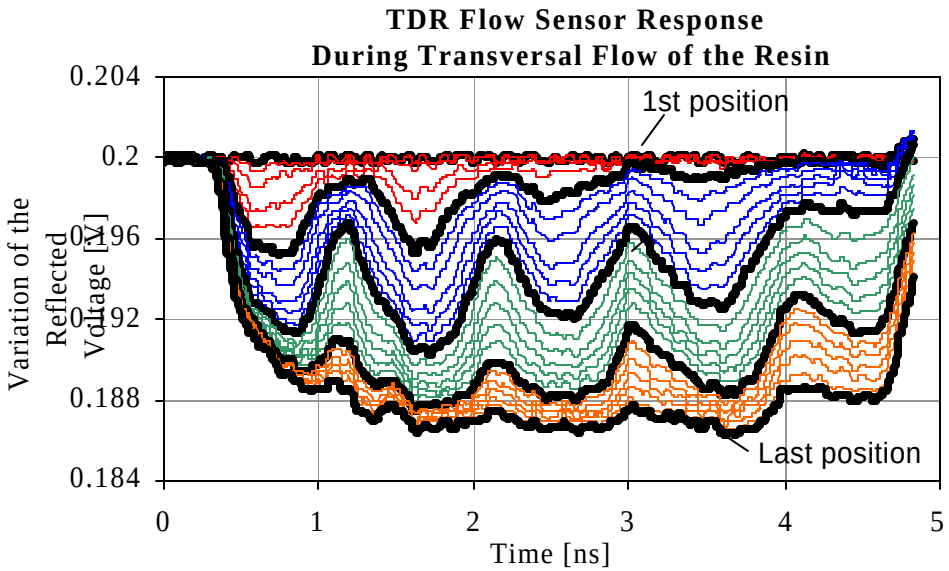
Surface coplanar transmission line gives very high sensitivity and high signal to noise ratio.



➔ **3mm accuracy has been demonstrated**

TDR Sensor
Detection of Multiple Flow Fronts





Time dependant locations of resin in the preform

Experimental data showing the movement of multiple flow fronts

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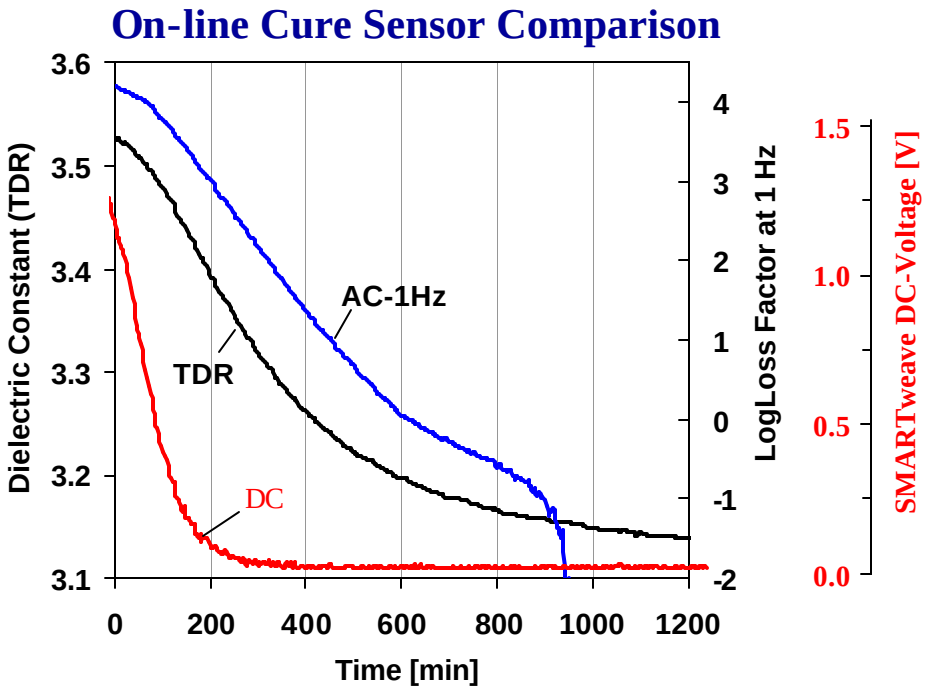
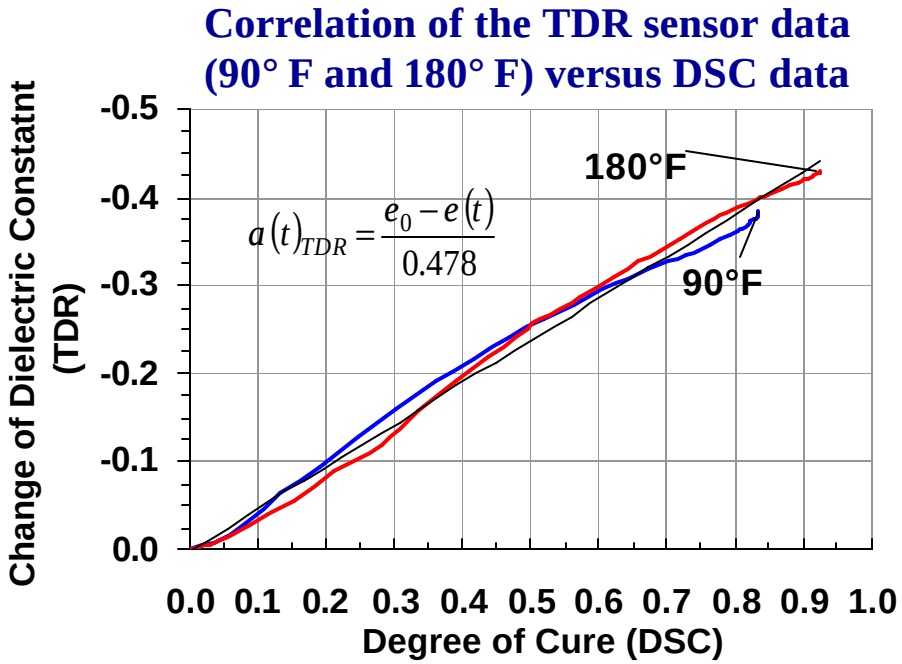
TDR Cure Monitoring





TDR CURE MONITORING ADVANTAGES

- Accurate on-line cure monitoring comparable to laboratory (FTIR and DSC) test equipment
- Low cost (flexible circuits can be mass-produced)
- Multiple sensor configurations for embedded or tool-mounted (reusable) versions are possible
- Sensing capability through intermediate layers: release agent, gel coat and others

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Motivation for an Intelligent VARTM Workcell

Current Industrial Practice

- Prototypes, not production
- Trial and error
- High variability
- No automation, sensing, or control
- Manufacturing base limited to a few companies with know-how
- Costs not competitive with traditional approaches
- No two parts the same

- Design/Modeling of Infusion
- Fundamentals of mixing of reacting systems
- Controlled infusion
  - Sensors
  - Actuators
  - Software
- Preform consolidation mechanics
- QA/QC

Implementation and Validation of an Intelligent VARTM Workcell

Technology Transfer

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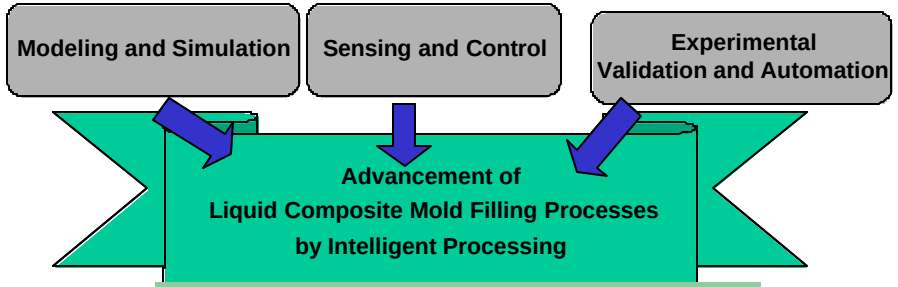
Intelligent Process Control

Intelligent Process Control requires
- Real-Time Process Evaluation
  - Real-Time Process Simulation
  - Integrated Sensors
- Maximize Automation
- Learning Capability
  - Network Capable

IPC system allows
- Repeatability
- Dimensional Control
- Scrap Reduction
- Eliminate Post-Inspection
- Increase Production Rates
- Process Traceability
  - QA/QC of Process
  - SPC
- Reduce Touch-Labor
- Reduce Cost



- Increase production repeatability
- Reduce trial and error in process design
- Improve quality
- Introduce control

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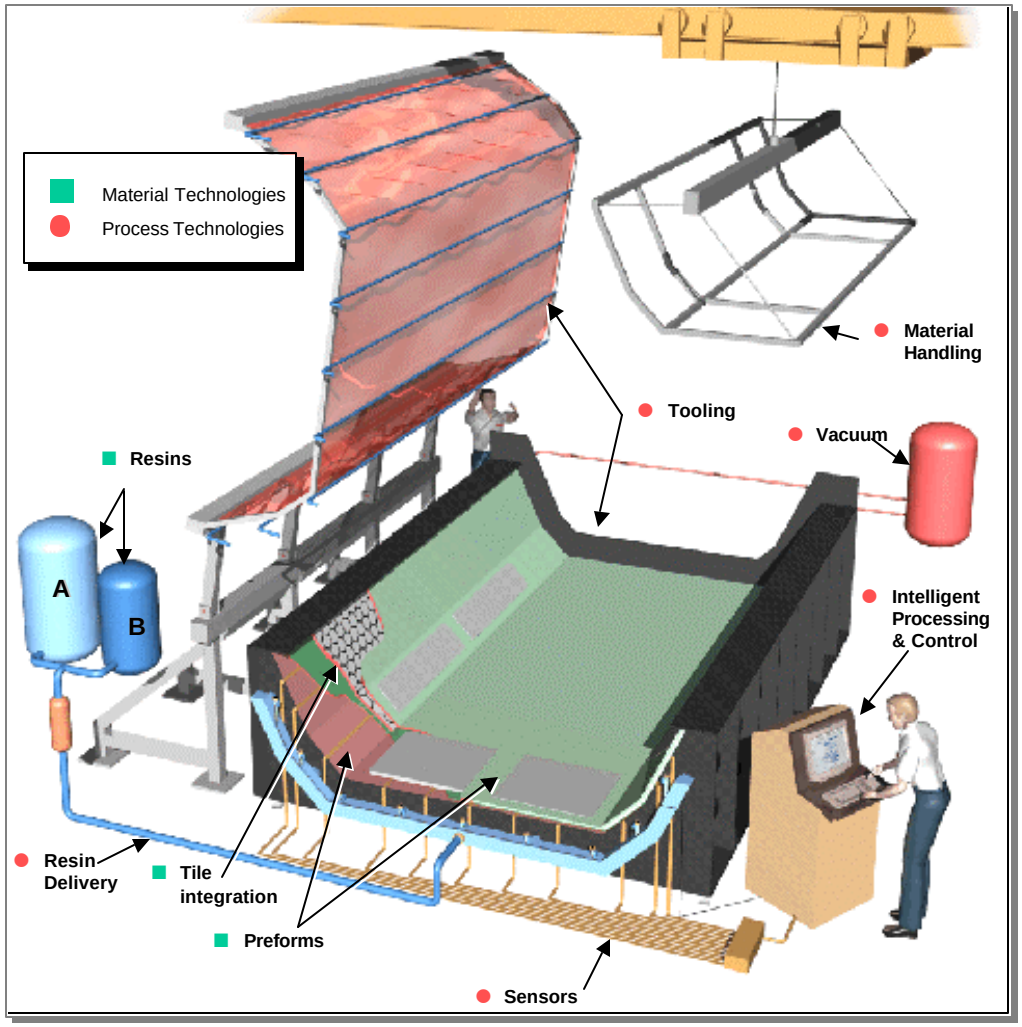
Schematic of a Fully Automated VARTM Production Cell

OBJECTIVES

- Automated Resin Delivery System
- Smart Tooling
  - Tool-Mounted Sensors
  - Resistive Heaters for Cure Control
- Automated Material Handling of Preforms
- Automated Vacuum Stations
- Reusable Bagging

➔ Intelligent Processing and Control

➔ Automation of all Processing Steps



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SMARTMolding Prototype Cell

1. Manual and AutomaticControl and Monitoring
   1. Pinch Valves
   2. Vacuum
   3. Precision Scales
   4. CCD-Camera
   5. Tool-Mounted SMARTMolding Sensors
2. Automation
   1. Sequential Injection Control with feedback from tool-mounted sensors

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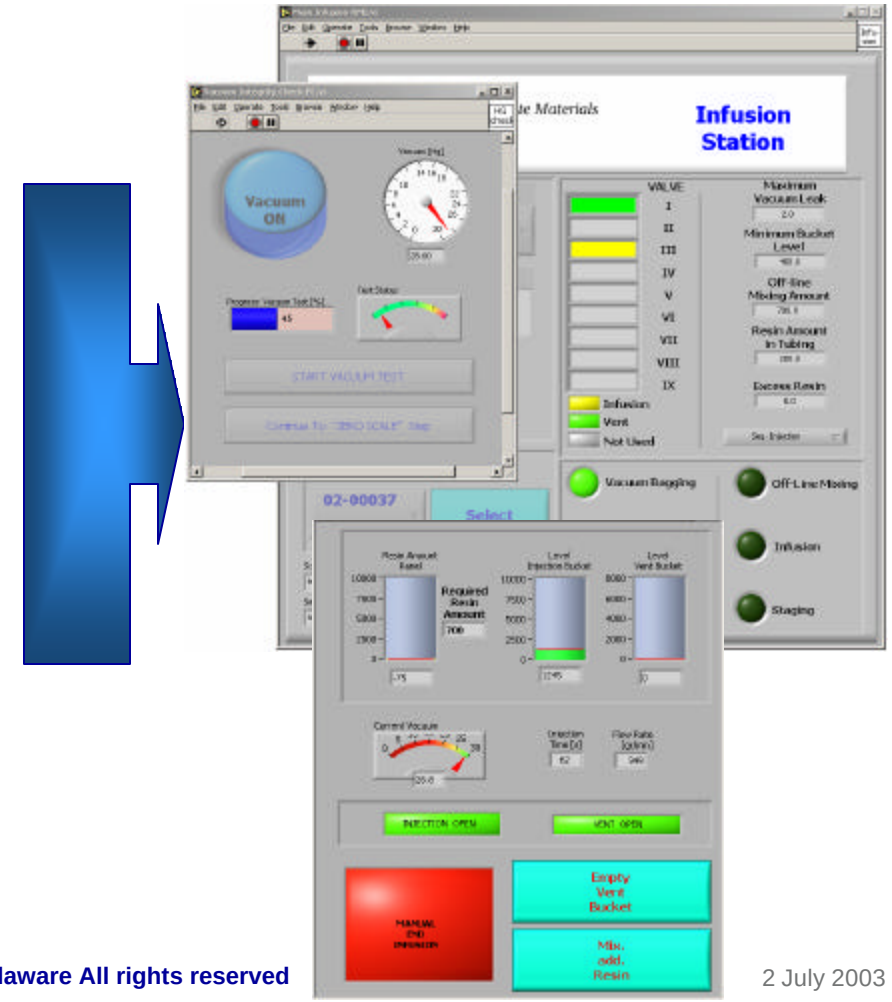
SMARTMolding
Full Production Cell



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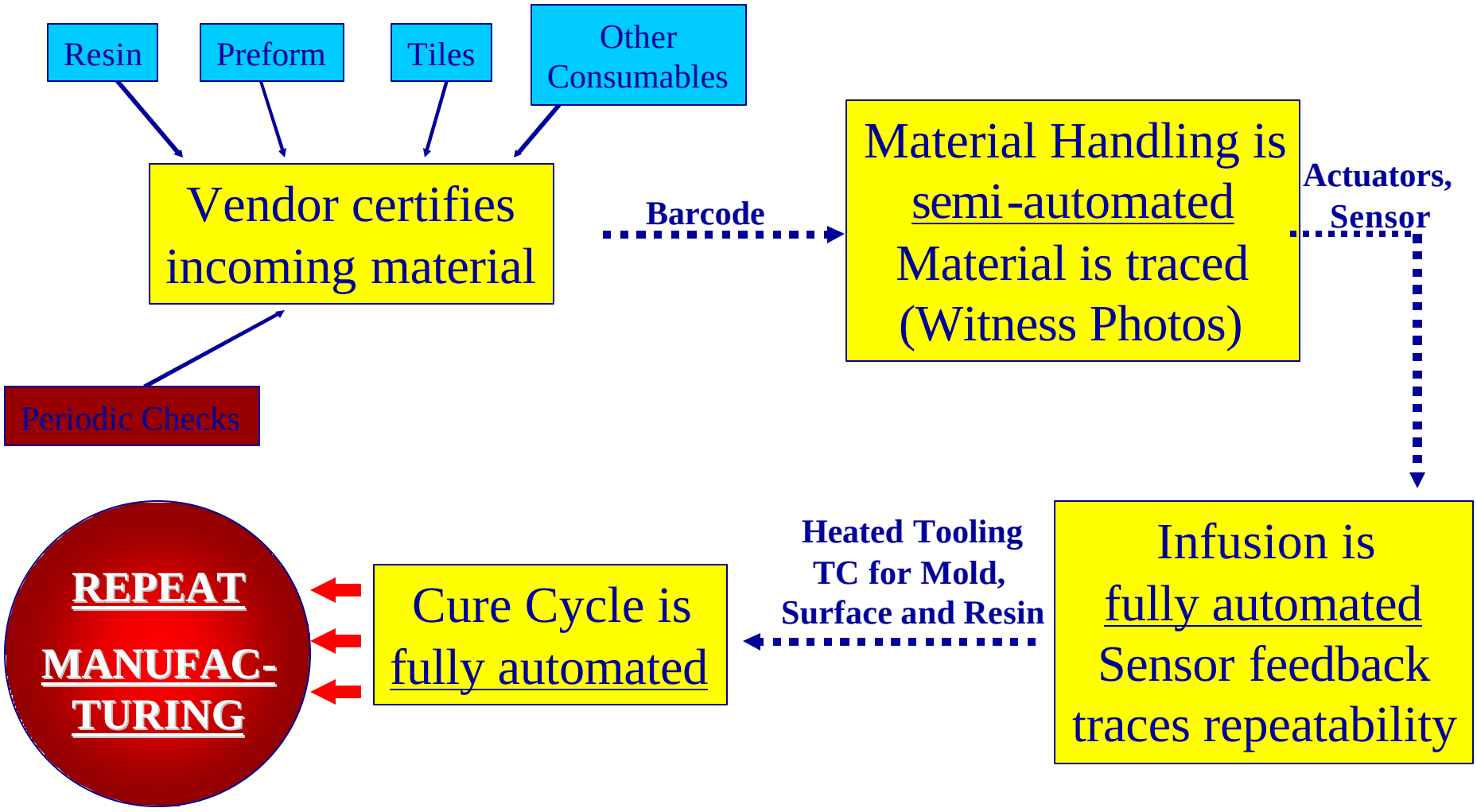
Automation, Sensing, & Incoming Material Control Allow Repeat Manufacturing



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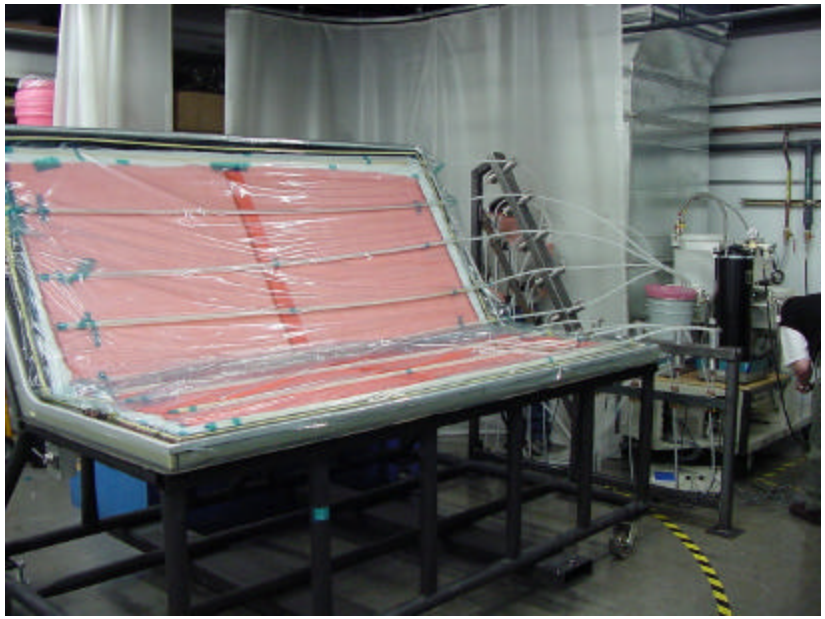
SMARTMolding Features

Automation Features

- Operator Login
- Shell Selection via Barcode
- Automated Tool Selection
- Automated Vacuum Control (Infusion, Dwell) and Leak Check
- Controlled On-Line and Off-Line Mixing
- Supervised Infusion
    - Sensor Feedback from tool-mounted and/or SMARTPad sensors
    - Fully Automated opening/closing of Valves
    - Script Files for Sequential Injection
        - Process Variation Easy to Implement
        - Allows Dwell of Last Infusion Lines
- Timed Dwell (Reduction in Pressure to 7Hg) is Automated
- Process and Sensor Information are stored for QA/QC



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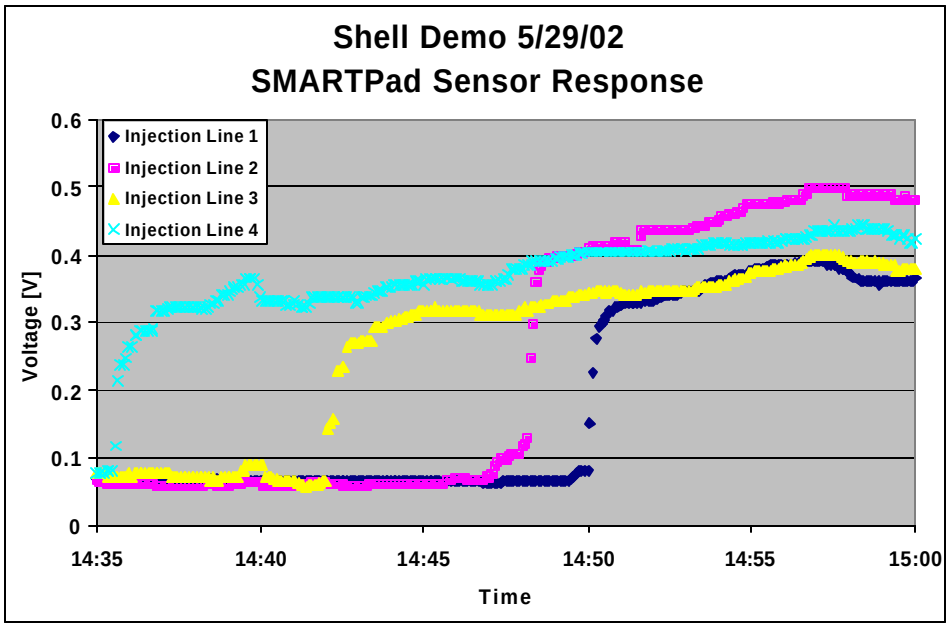
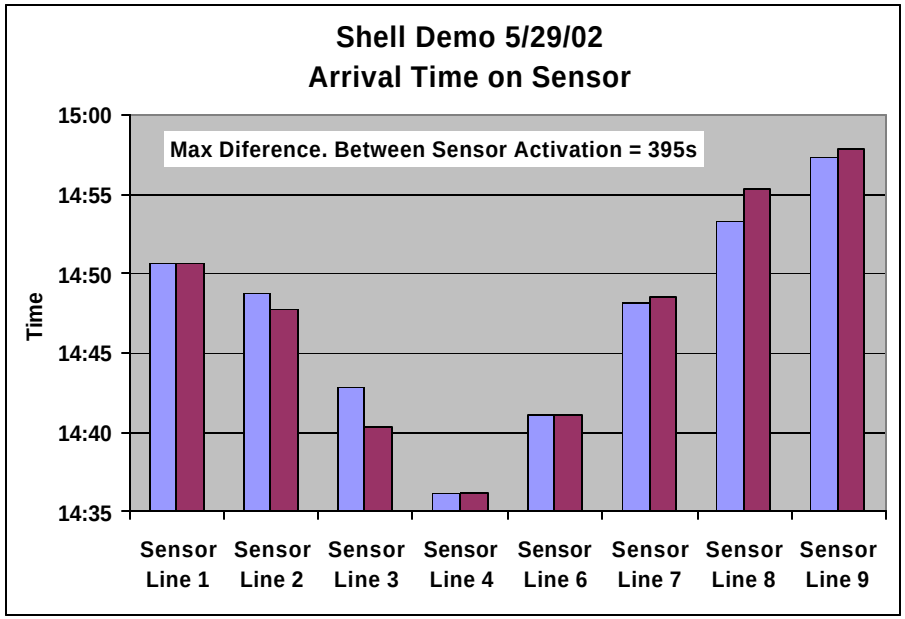
SMARTPad Sensor Info



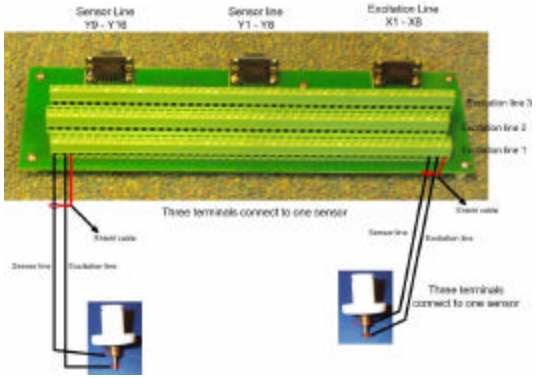


Two SMARTPad sensors under each injection line was attached to tool

New PC board was developed for simple connectorization

Sensor response indicates

- **Arrival time at each sensor**
  - **SPC**
  - **Optimization of Infusion Scheme**
- **Uniformity of fabric permeability**



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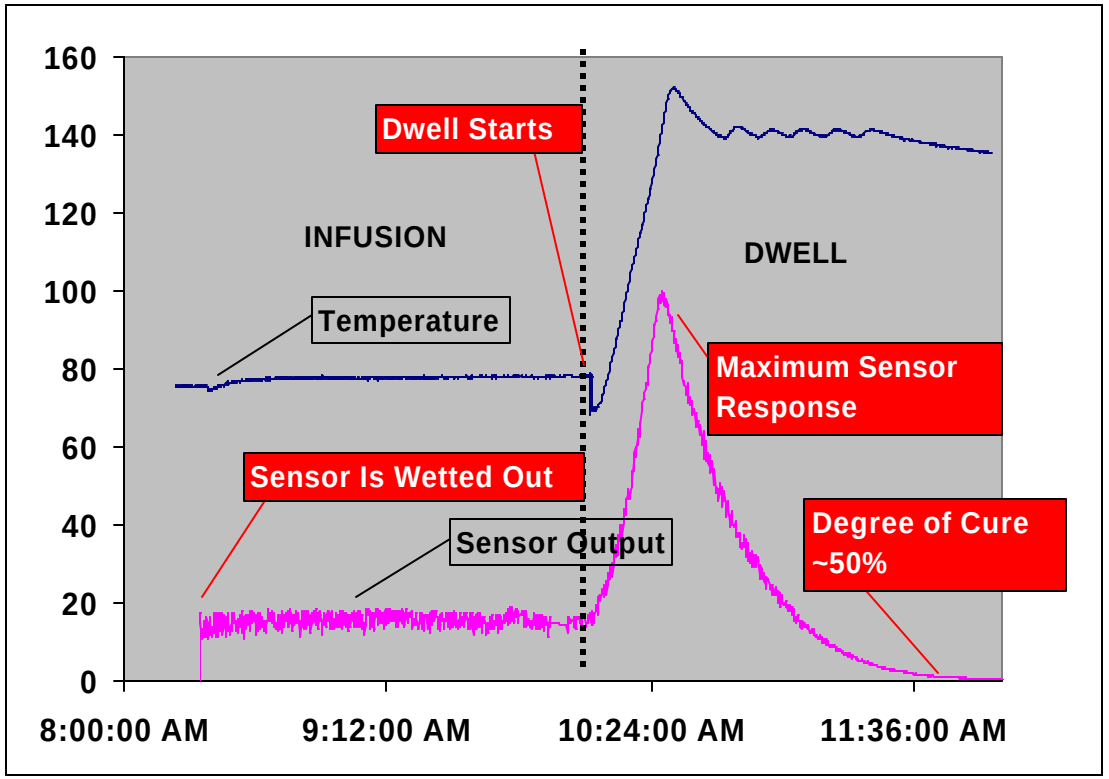
SMARTMolding Cure Monitoring

New Tool-Mounted Torlon Sensor
New Embedded or
Surface Mounted Flexible Circuit Sensor



Monitors resin arrival

The degree of cure can be observed up to 50%

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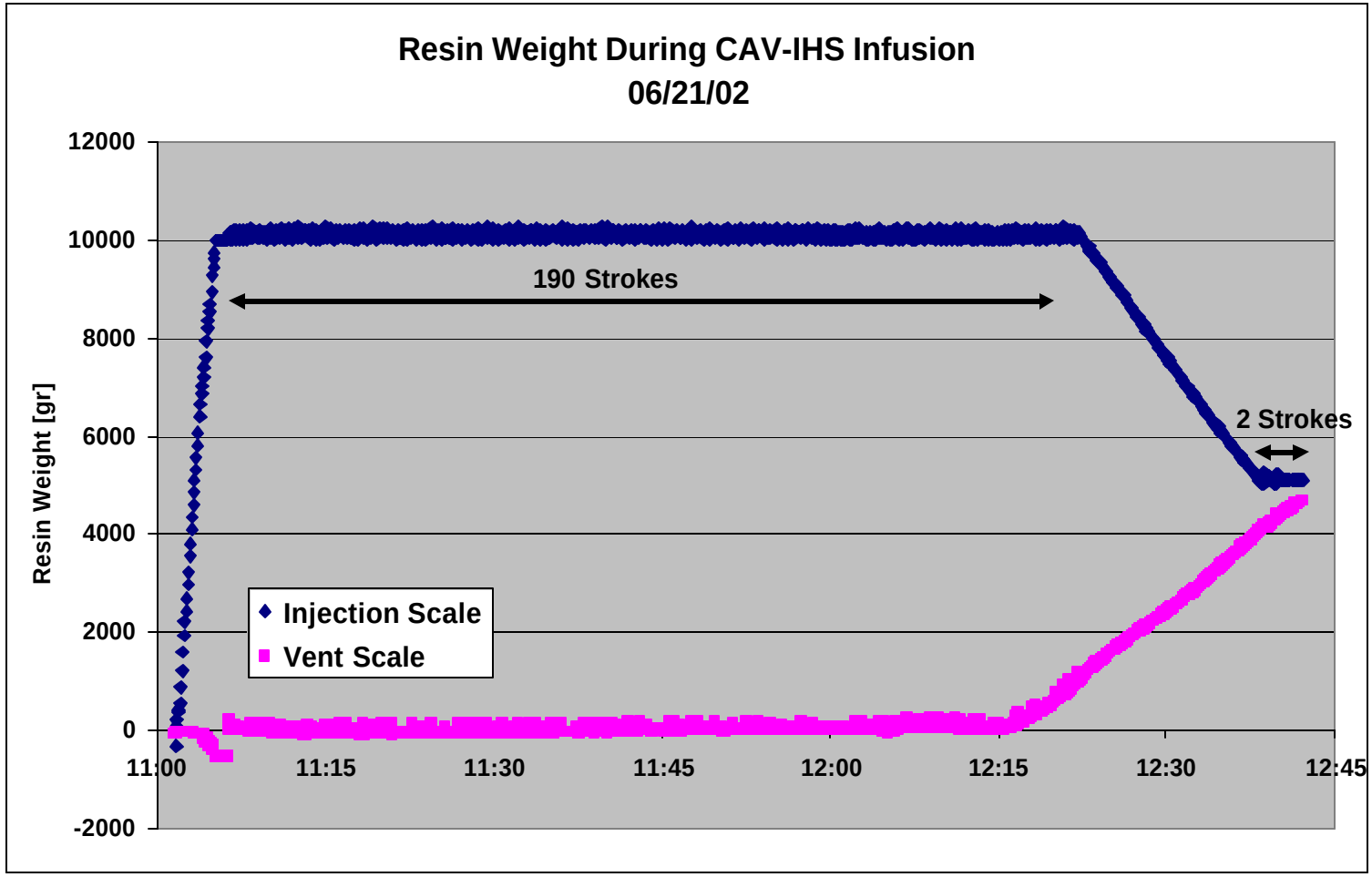
Automated On-Line Mixing
CAV-IHS Shell Infusion



TOTAL Automated Infused Weight: 128lb

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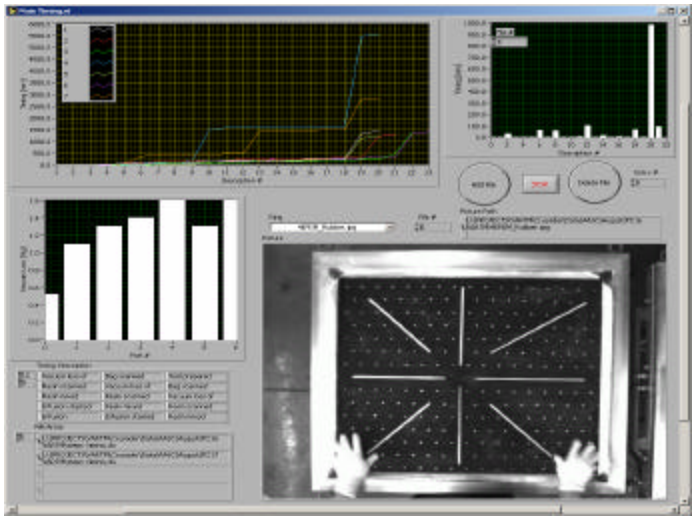
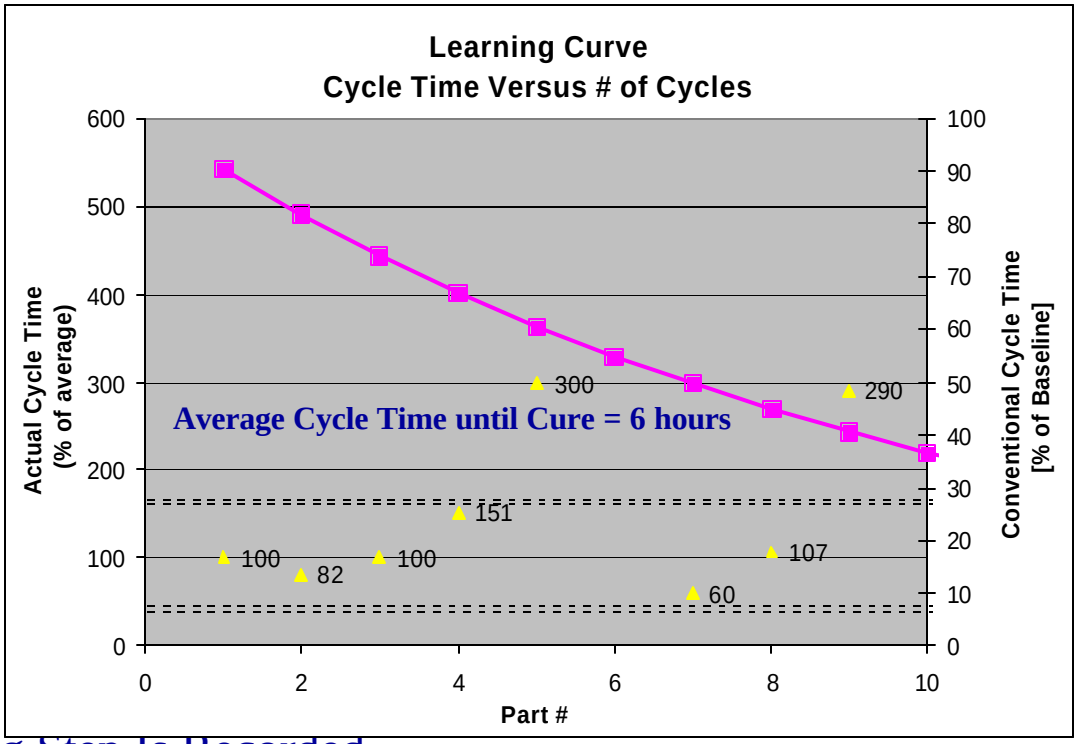
Sensor Data Review
Timing





Automation enables repeatable ➔ processing times from cycle 1

- Individual Time For Each Processing Step Is Recorded
- Witness Photo Of Tool Fill Is Displayed
- Vacuum Loss During Vacuum Check Is Shown

➔ Request for Operator Comment when Actual Time Step is Larger Than Nominal

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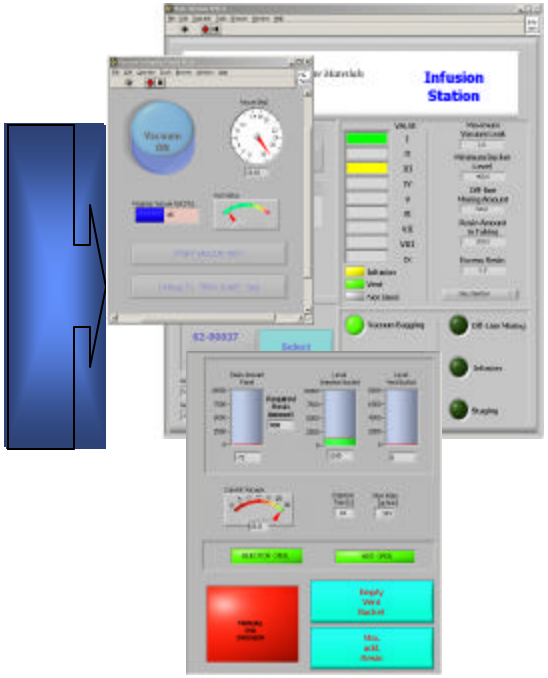
Implementation

Hardware

- Pinch Valves
- Vacuum Control and Sensing
  - Leak Check
- Sensors
  - Temperature
  - Flow
  - Cure
  - Scales for Flow rate

Software



- Recipes
- QA/QC Database
- Graphical User Interfaces
  - Material Lay-up
  - Infusion
  - Cure Control

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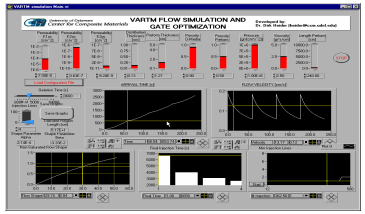
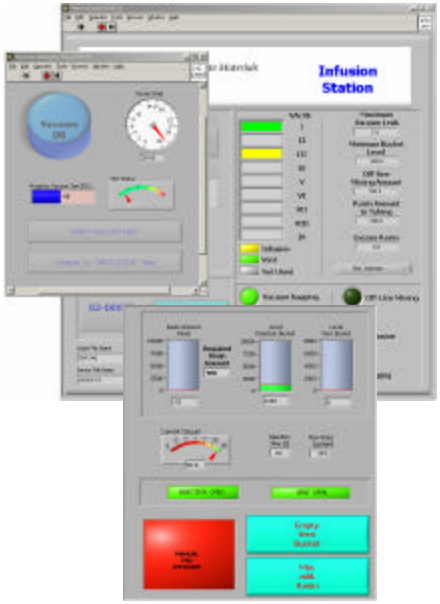
SMARTMolding Software Suite

Design Tool



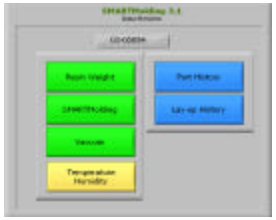
Simple Interface, Limited to simple geometries
Predicts Flow Times, Lead Length
Optimizes # of Seq. Injection Lines
Database with Material Properties

IPC System

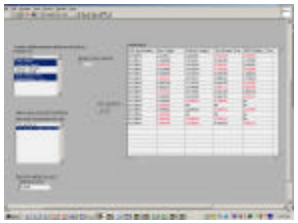


Automates the VARTM Process
Records the processing steps
Reporting of collected data
Enables statistical analysis
Guidance Software to define process recipe

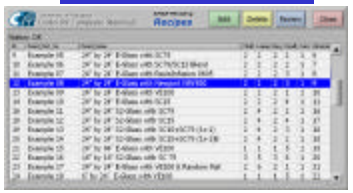
Data Review



Statistical Package



Recipe GUI



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Database Overview

Configuration Tables

- Setup (directories, DAQ settings)
- Material Info (Resin, Fabric, Core)
- Operator Info

Recipe Tables

- Material Sequence
- Bag and Tool Selection
- Infusion Information
  - Max. Leak
  - Resin Info (Amount, Type, Ratios)
  - Sensor Setup
  - Seq. Infusion Script (Valves ←→ Sensors)
- Dwell Info (Temperature, Time)

QA/QC Tables

For each part
- Sensor Feedback
- Cycle Time

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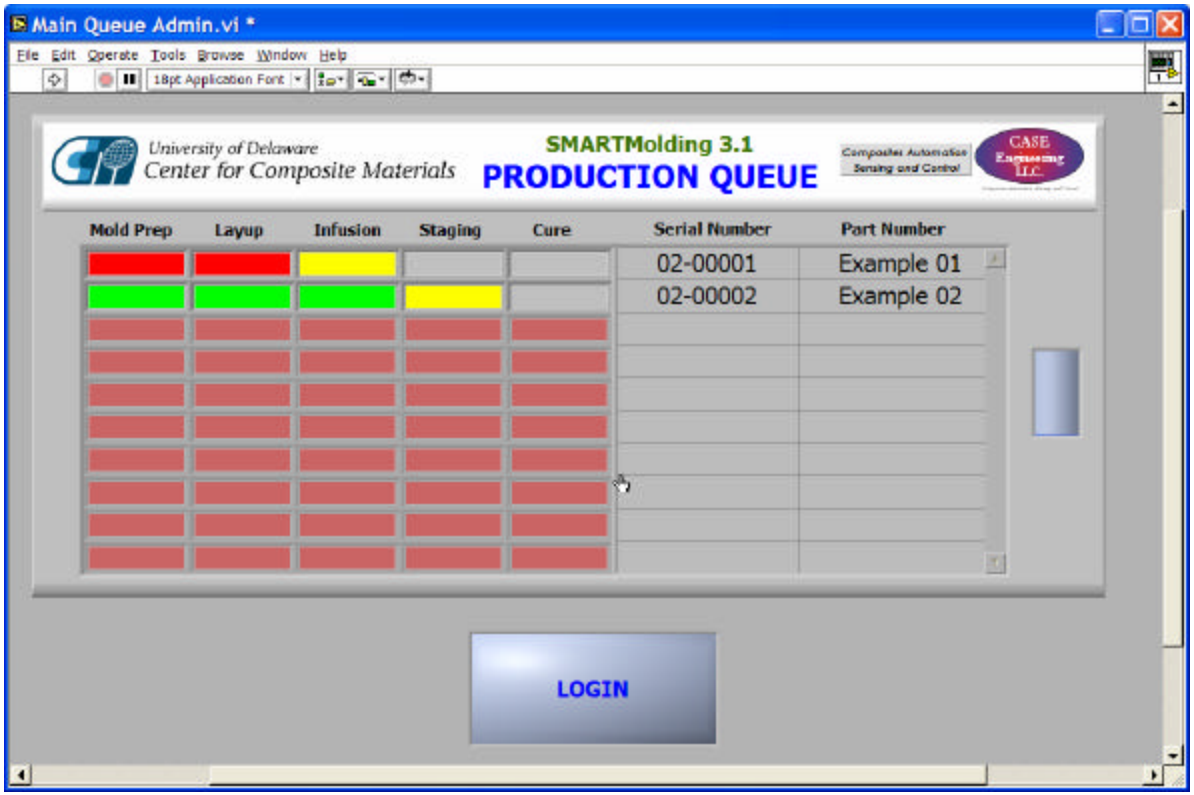
Manufacturing Queue



- Allows central administration of VARTM production
- Enables monitoring of production status

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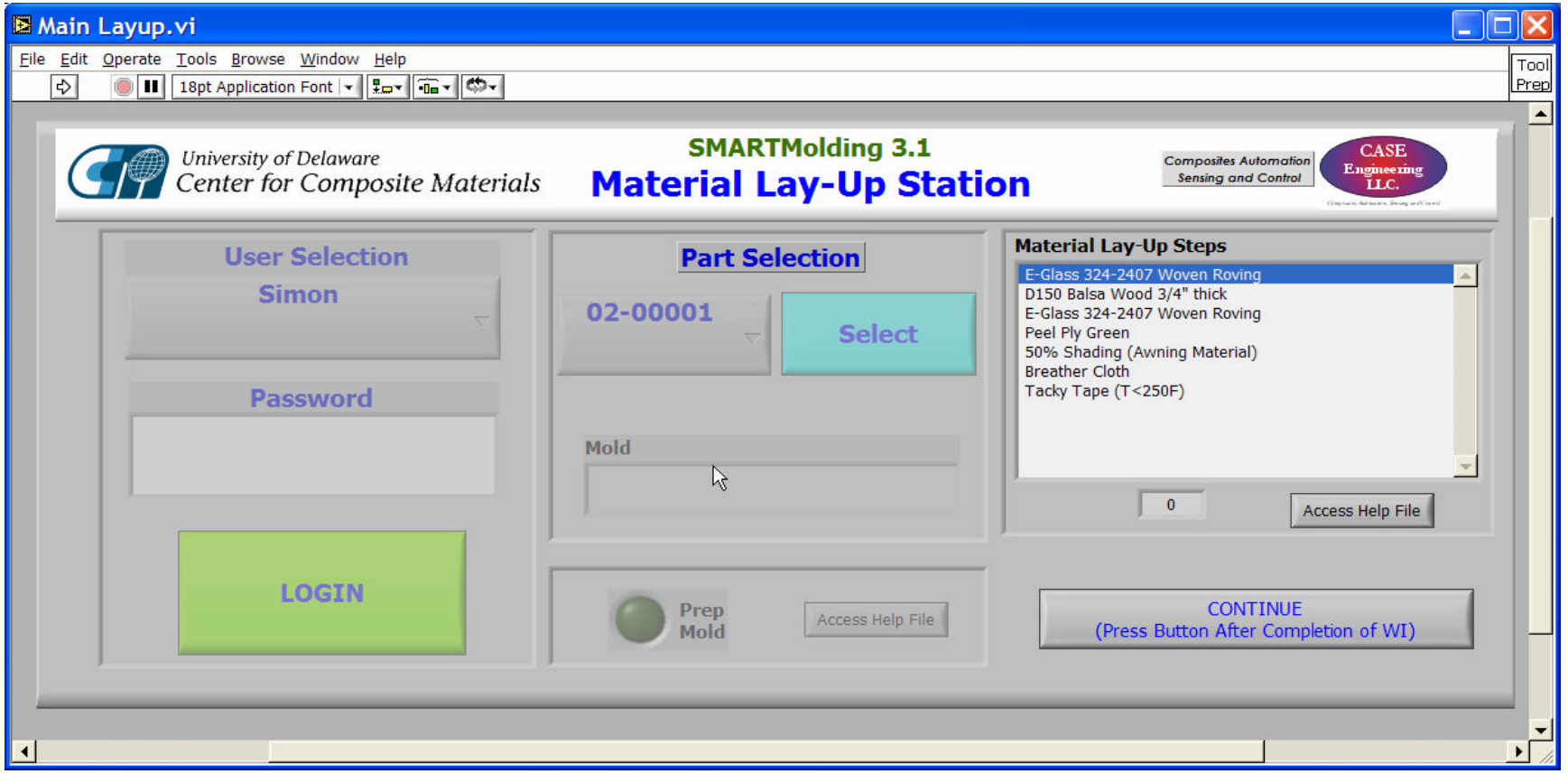
Material Lay-up Station



- Login feature
- Automatic part selection
- Recording of cycle time
- On-line help via work instruction

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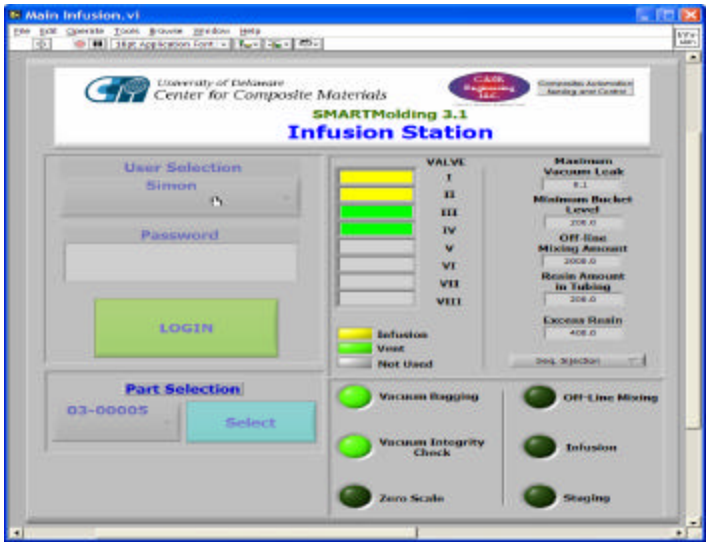
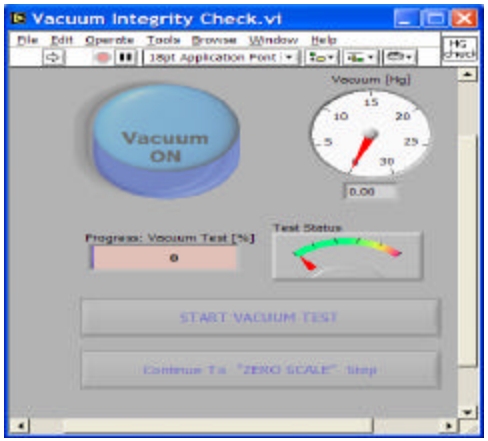
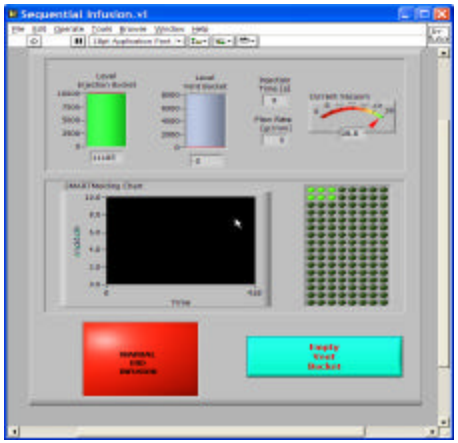
Infusion Station



(a)

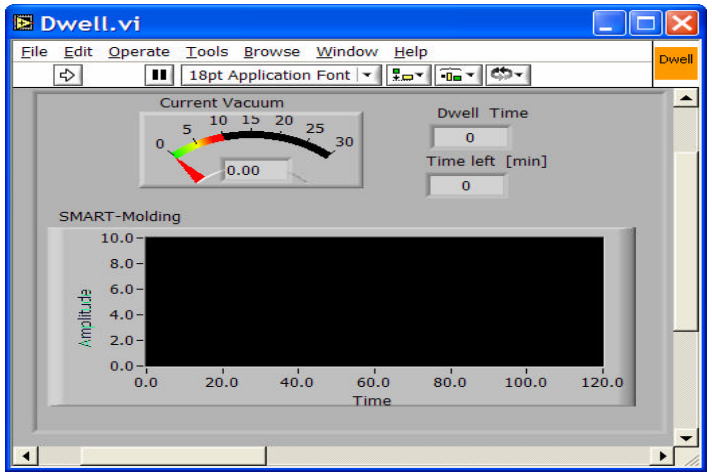


(b)



(c)

- Login feature
- Automatic part selection
- Recording of cycle time
- On-line vacuum integrity check (Figure b)
- Allows integration of industrial mixer hardware
- Sequential Injection automation (Figure c)
- Timed room-temperature dwell (Figure d)
- Records sensor feedback



(d)

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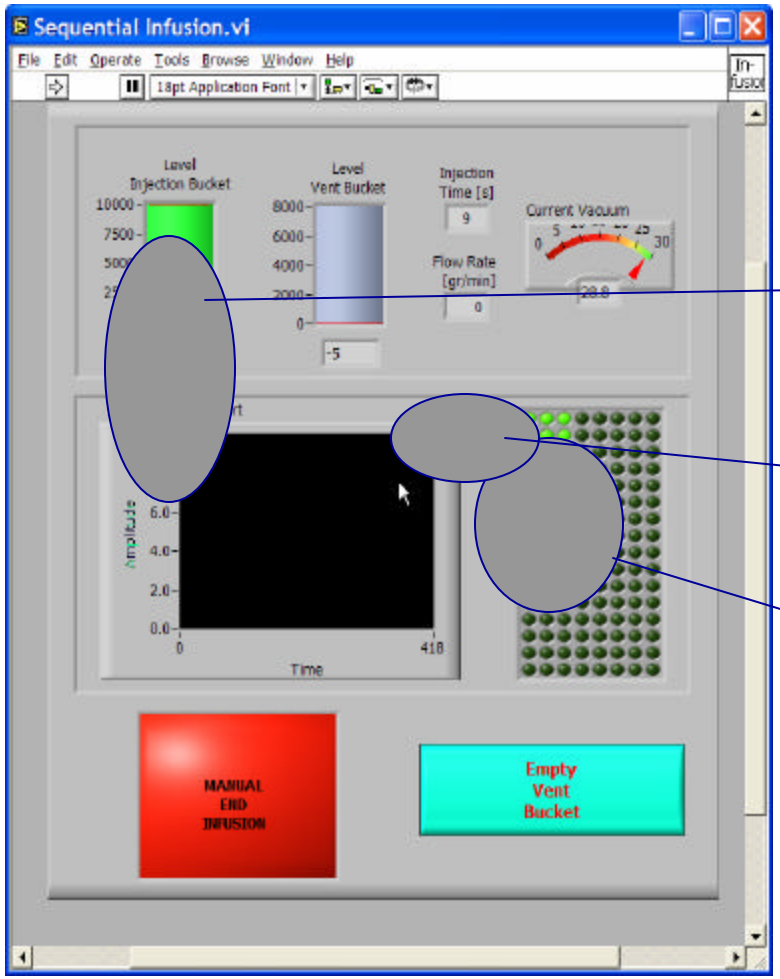
Automated Infusion End



A) Minimum Resin Amount Infused

B) Net gain into Part below 10gr/min

C) All sensors are wetted out

➔Infusion stops when

A ^ B ^ C = TRUE

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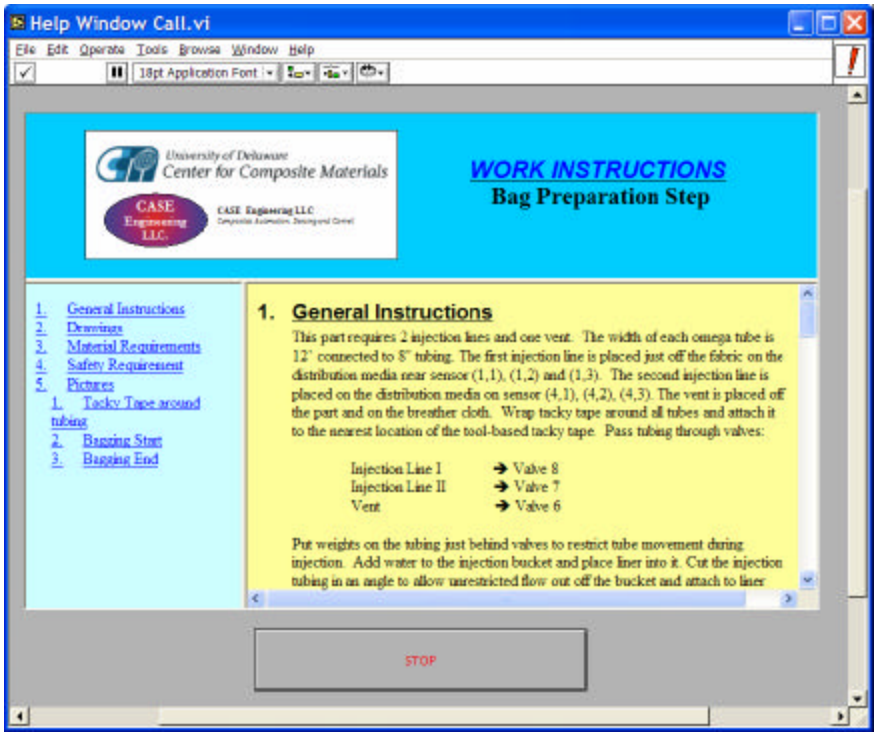
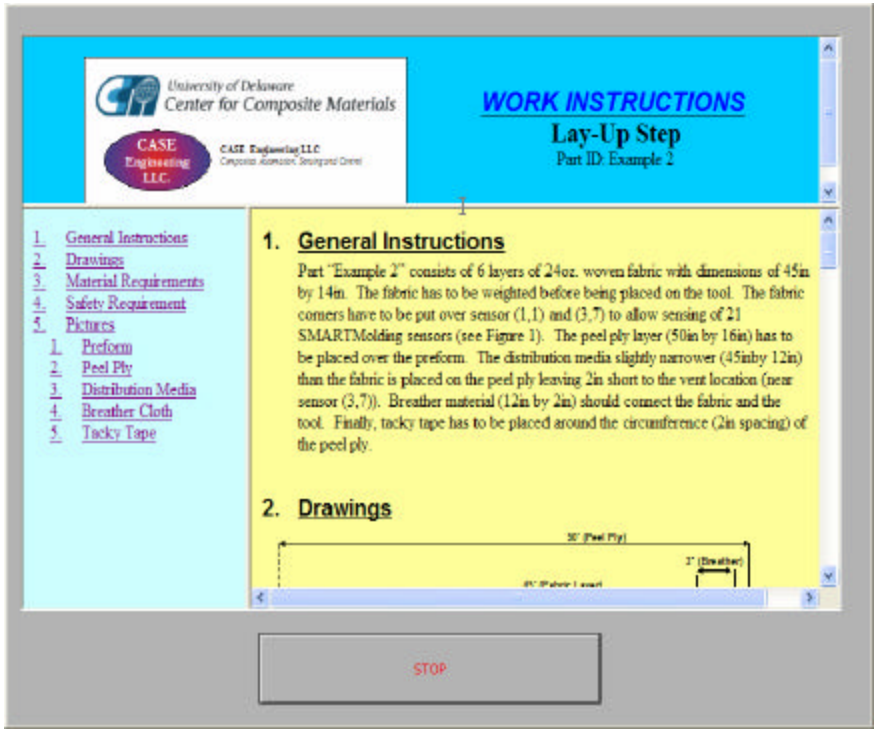
Help Through Work Instructions



Lay-up



Infusion

- Includes instructions about lay-up, infusion and staging using HTML
  - MSDS
  - Pictures
  - AutoCAD drawings
  - Video

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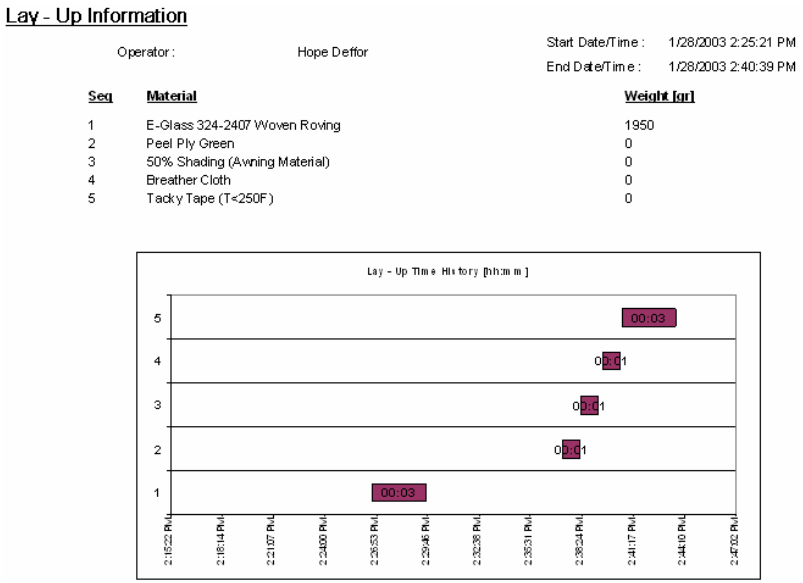
Report



Lay - Up Information

Operator: Hope Deffor

Start Date/Time: 1/28/2003 2:25:21 PM
End Date/Time: 1/28/2003 2:40:39 PM

Seq	Material	Weight [gr]
1	E-Glass 324-2407 Woven Roving	1950
2	Peel Ply Green	0
3	50% Shading (Awning Material)	0
4	Breather Cloth	0
5	Tacky Tape (T<250F)	0

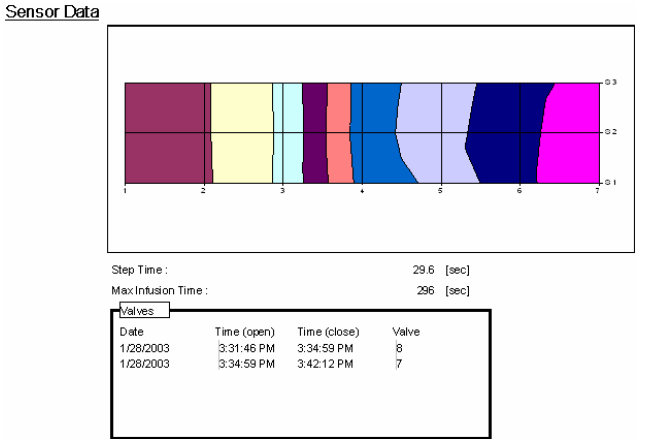
Status Information

Operator: Dirk Heider

Start Date/Time: 1/28/2003 12:12:02 PM
End Date/Time: 1/28/2003 12:12:02 PM

Calculated Fiber Weight-Fraction:	0	[%]
Final Part Weight:	0	[gr]
Total Production Time	12:00:00 AM	[hh:mm]

Comments



Sensor Data

Step Time: 29.6 [sec]
Max Infusion Time: 296 [sec]

Valves

Date	Time (open)	Time (close)	Valve
1/28/2003	3:31:46 PM	3:34:59 PM	8
1/28/2003	3:34:59 PM	3:42:12 PM	7

- Basic Information
  - Operator
  - Material Sequence during Lay-up with Cycle Time Info
  - Opening/Closing of Valves
  - Weight and Fiber Volume Info
- Charts
  - Cycle Time for each processing step
  - Arrival Time of Flow Sensors

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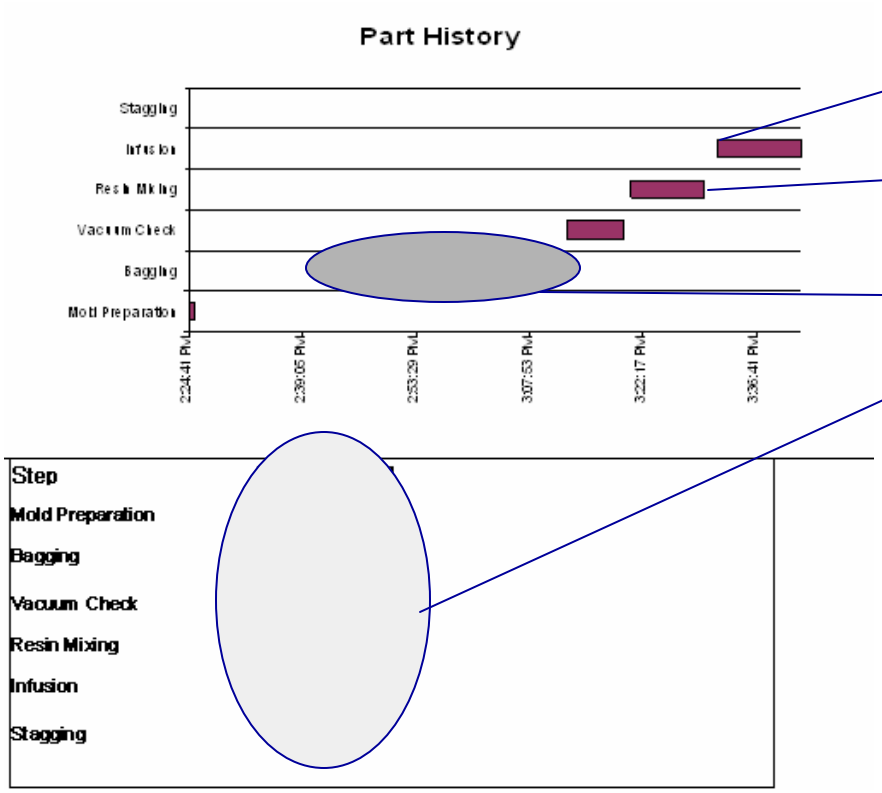
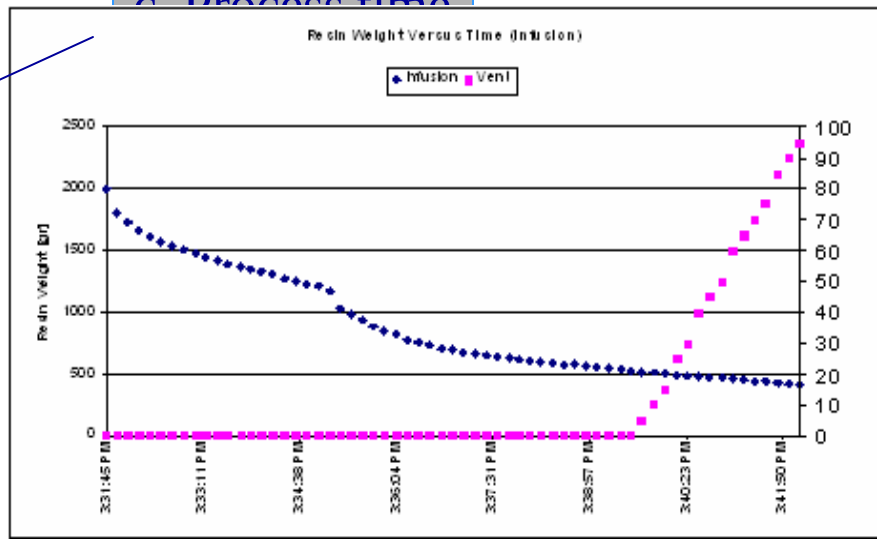
Infusion History Report



a. Start time

b. End time

c. Process time



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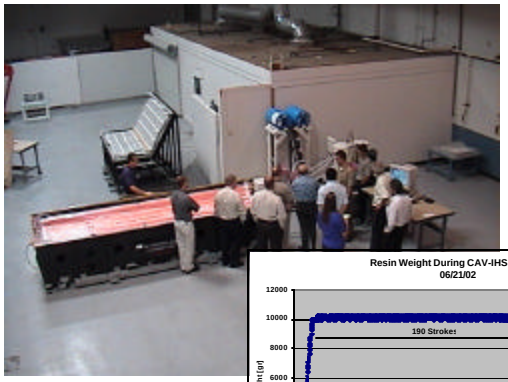
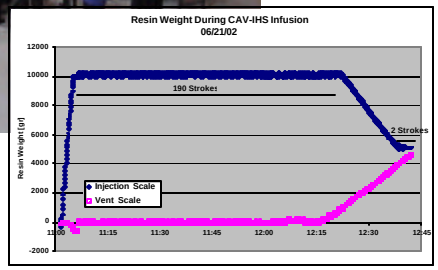
IPC Demonstration
PEGASUS / CAV IHS

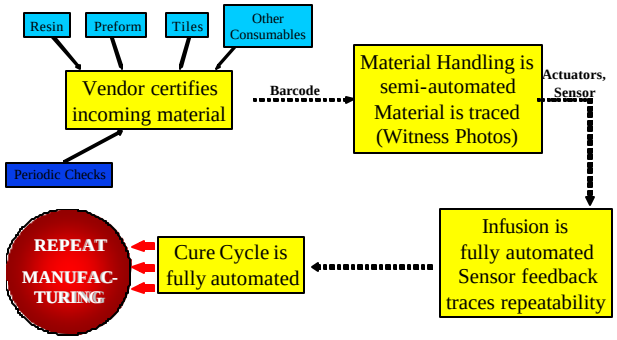


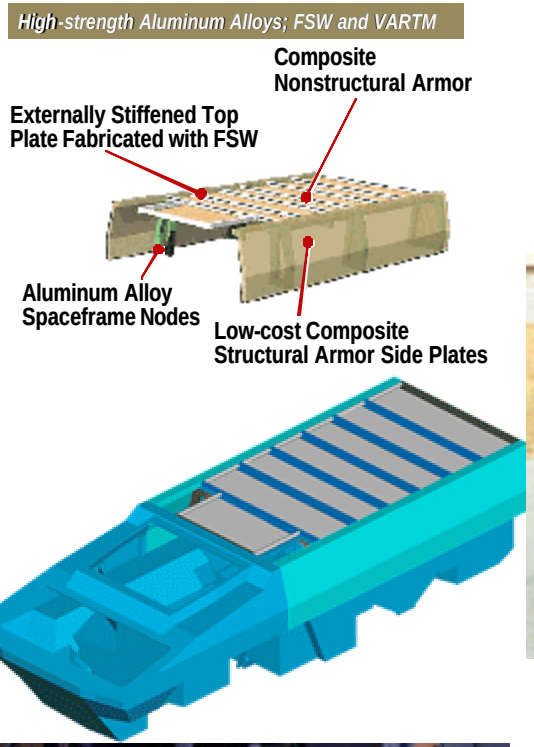


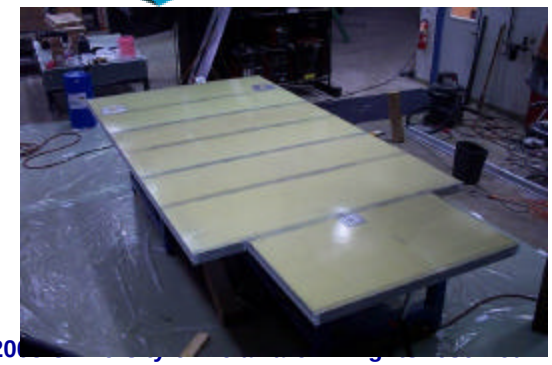
TOTAL Automated

Infused Weight: 128lb

SOFTWARE







- **Wheeled Platform Offer Breakthrough Technologies**

- **Vehicle Helps Army Meet 2008 FCS Timeline**
- **Wheeled Vehicle Designed and Built In Less Than 8 Months**

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Fun to Watch!!!

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BETA-Site Technology Transition